HYP2018

June 24 - 29, 2018

A quest for the “Kpp” bound state via ^{3}He(K^{-}, n) reaction, J-PARC E15 experiment

for E15 collaboration

M. Iwasaki

RIKEN
Cluster for Pioneering Research
Meson Science Lab.

J-PARC E15

Strong $\bar{K}N$ attraction! $\Lambda(1405)$ = K⁻p bound state?

Many theoretical supports for the existence!

Key questions : → excellent introduction by Prof. Dote *etc*.

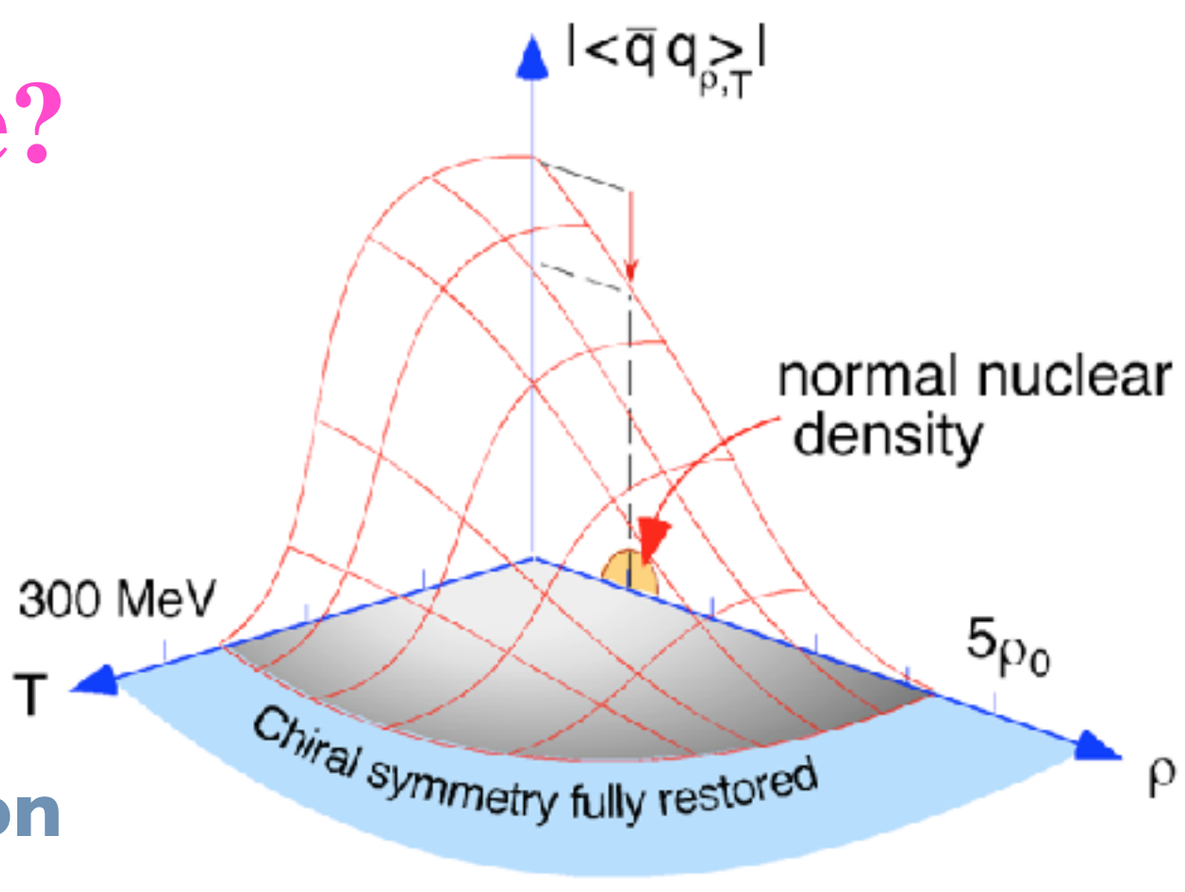
- Can kaon (boson) be a member of nuclei?

- Kaon properties change in nuclear media?

- Size of kaon bound state?

Could be a good probe for cold & dense QCD, to study the relation of hadron mass and χ-symmetry

<q̄q> as QCD-Higgs condensation



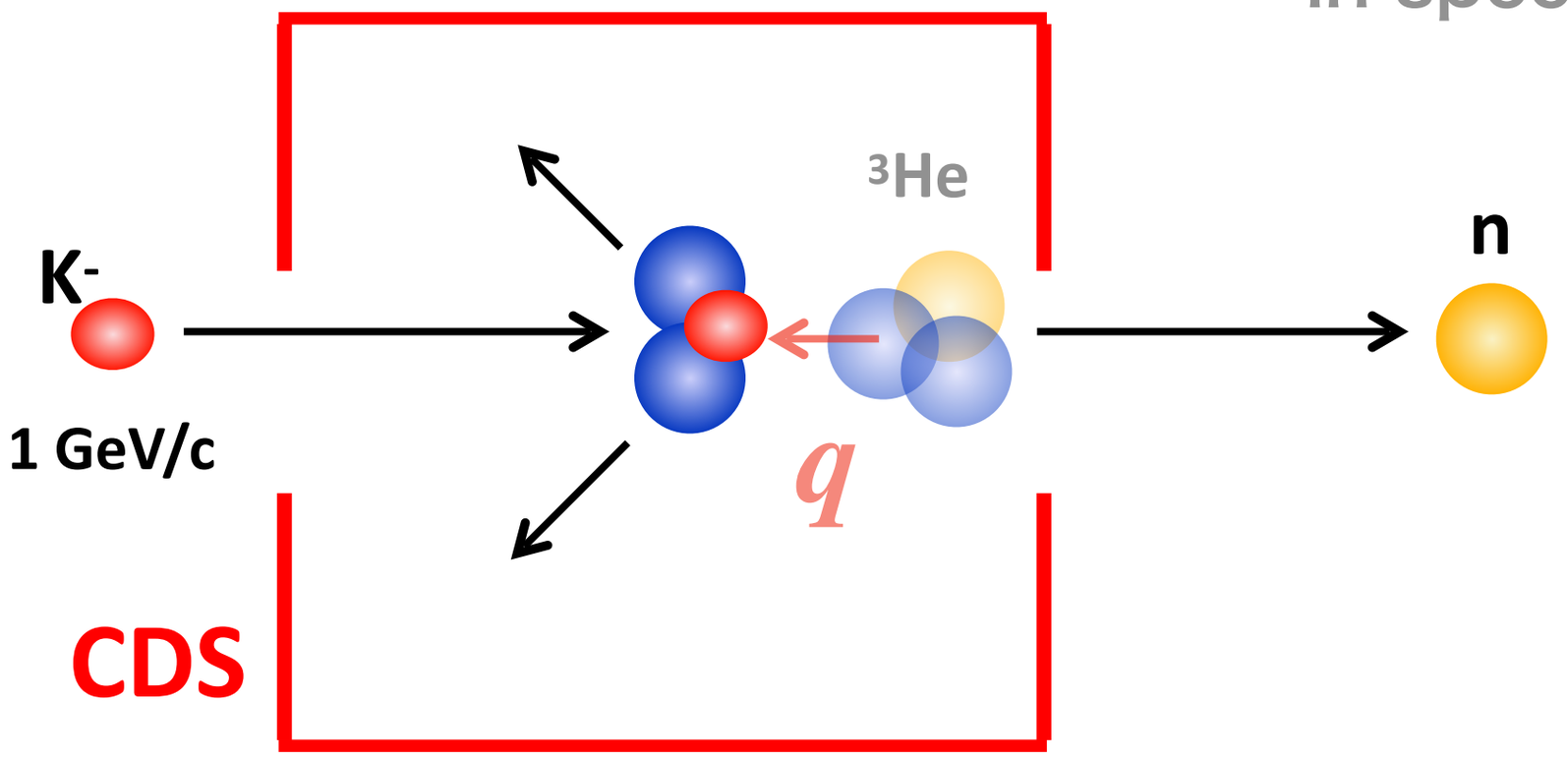
Semi-inclusive forward n

Prog. Theor. Exp. Phys. **2015**, 061D01 (11 pages)
DOI: 10.1093/ptep/ptv076

$$q = p_n - p_K$$

q: virtual kaon momentum

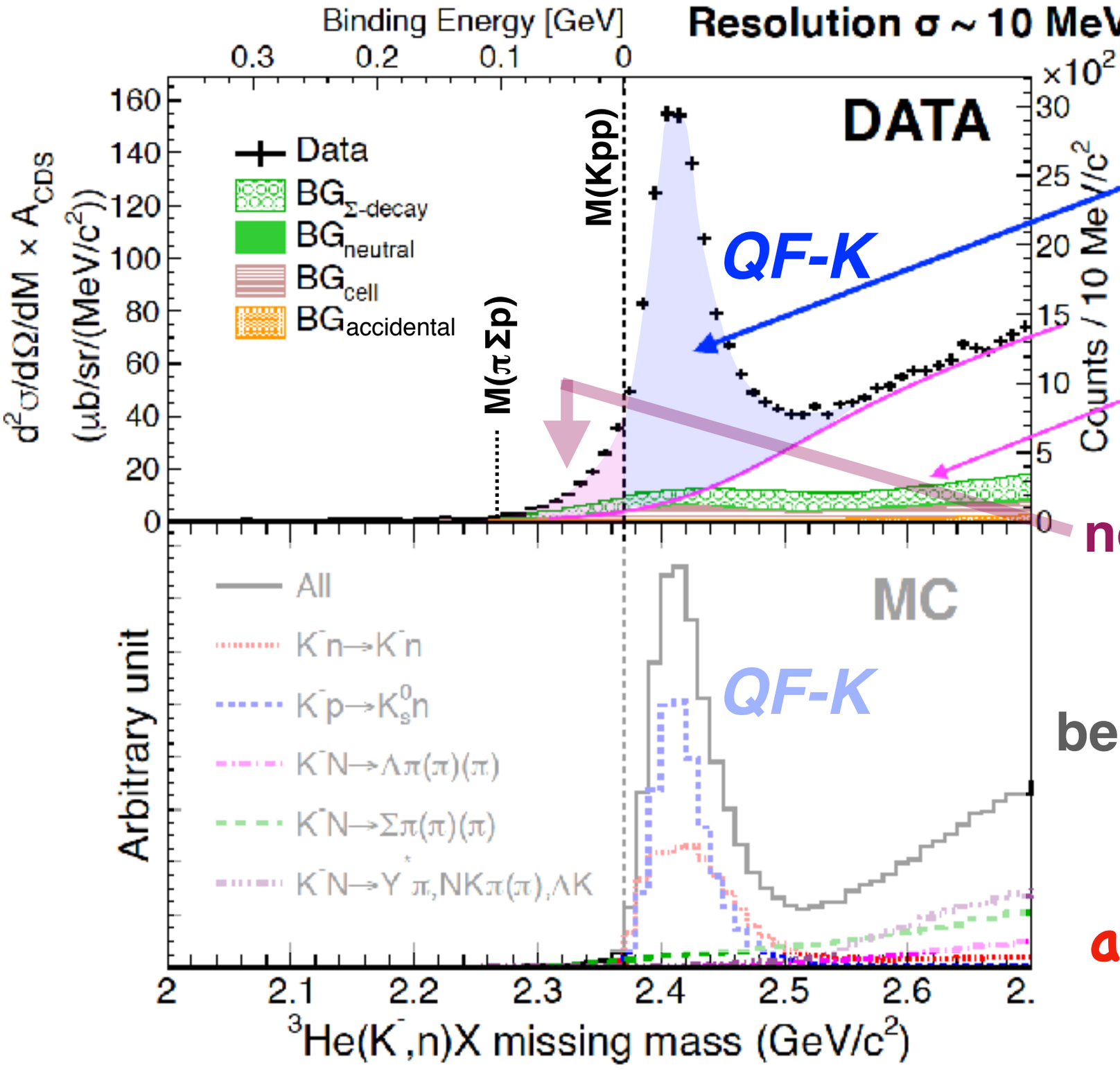
in spectators' frame



NC

Does
quasi-free kaon **(= "virtual kaon")**
stick to two spectator proton? **@ q~200 MeV/c**

Semi-inclusive forward n



KN→KN

Quasi-Free Kaon

$K^- + {}^3He \rightarrow K^0 + d_s + n$

$K^- + {}^3He \rightarrow K^- + 2p_s + n$

Hyperon decay

$K^- + {}^3He \rightarrow Y + \pi(\pi)(\pi) + 2N_s$

$Y \rightarrow n + \pi$

not clear signal observed,
where we expected
large yield ~ 1 mb/st
below the threshold M(Kpp)
but we larn

KN interaction is:
absorptive & attractive!

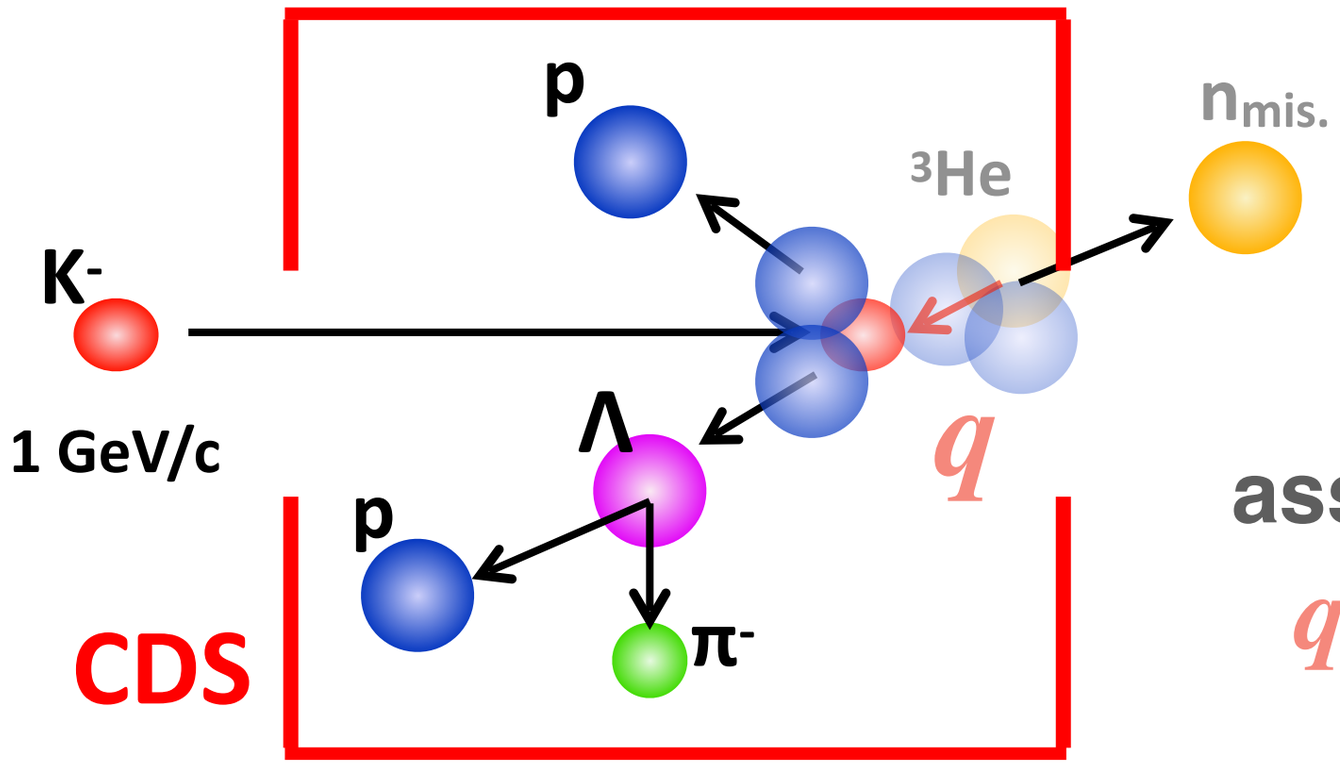
QF-K is dominant

KN→KN

Exclusive: Λ p n

simplest final state

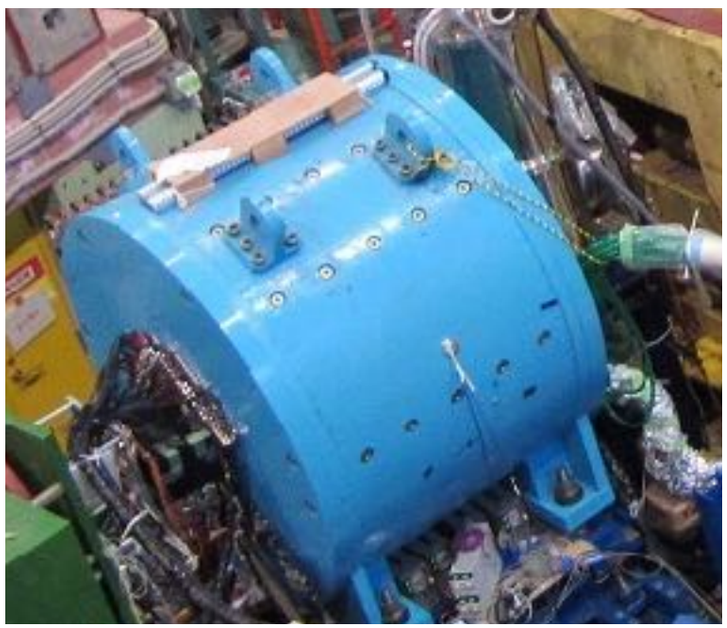
3 baryon w/ strangeness



assuming KN→KN

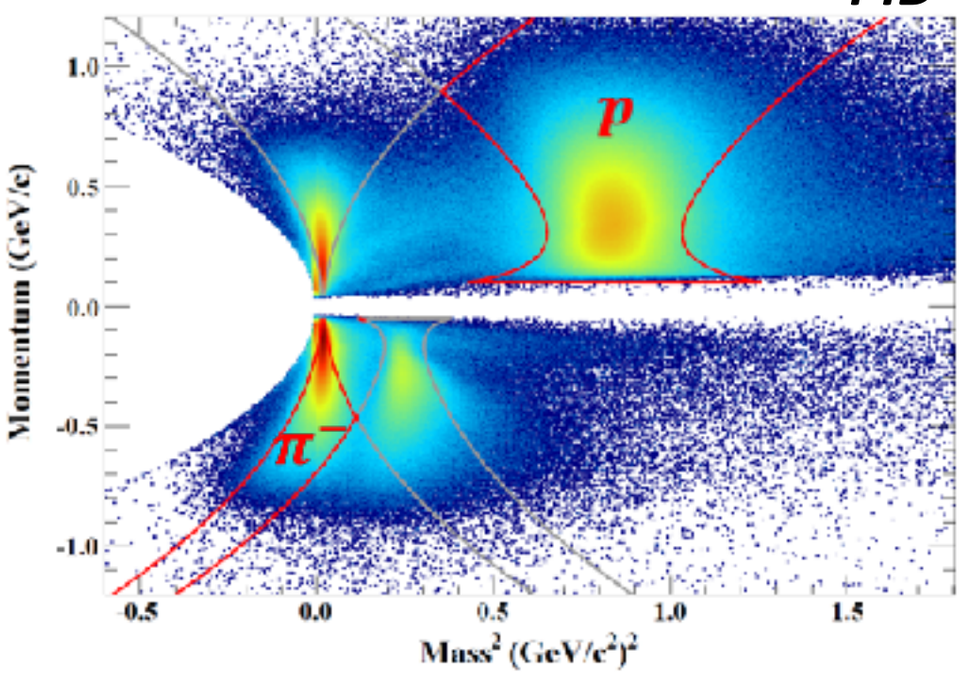
q: virtual kaon momentum

$K^- + {}^3He \rightarrow (\Lambda + p) + n$



Λpn final state w/ 4-momentum conservation

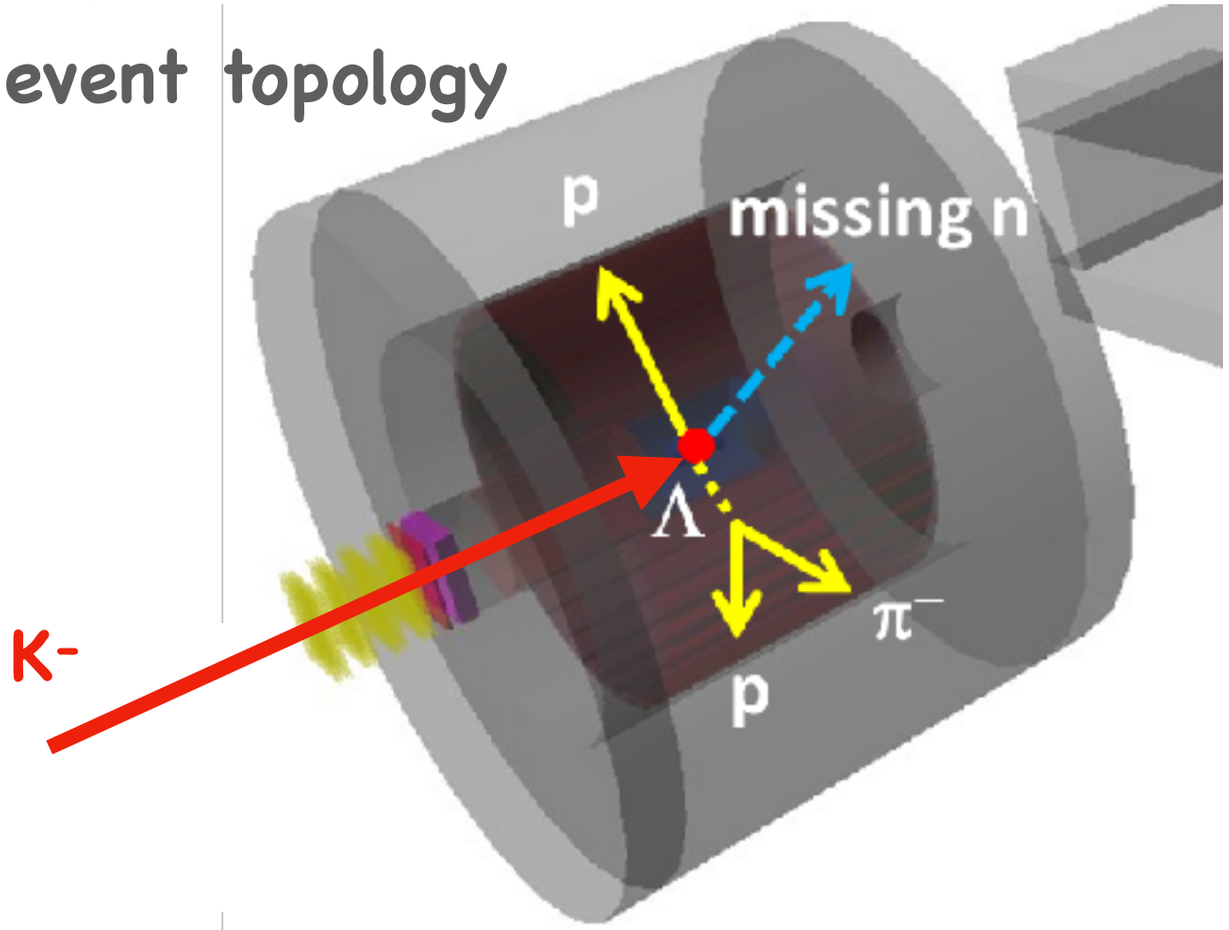
PID



Λpn event selection from "ppπ⁻ events"

with single cut

event topology



lnL: product of 6 probability densities

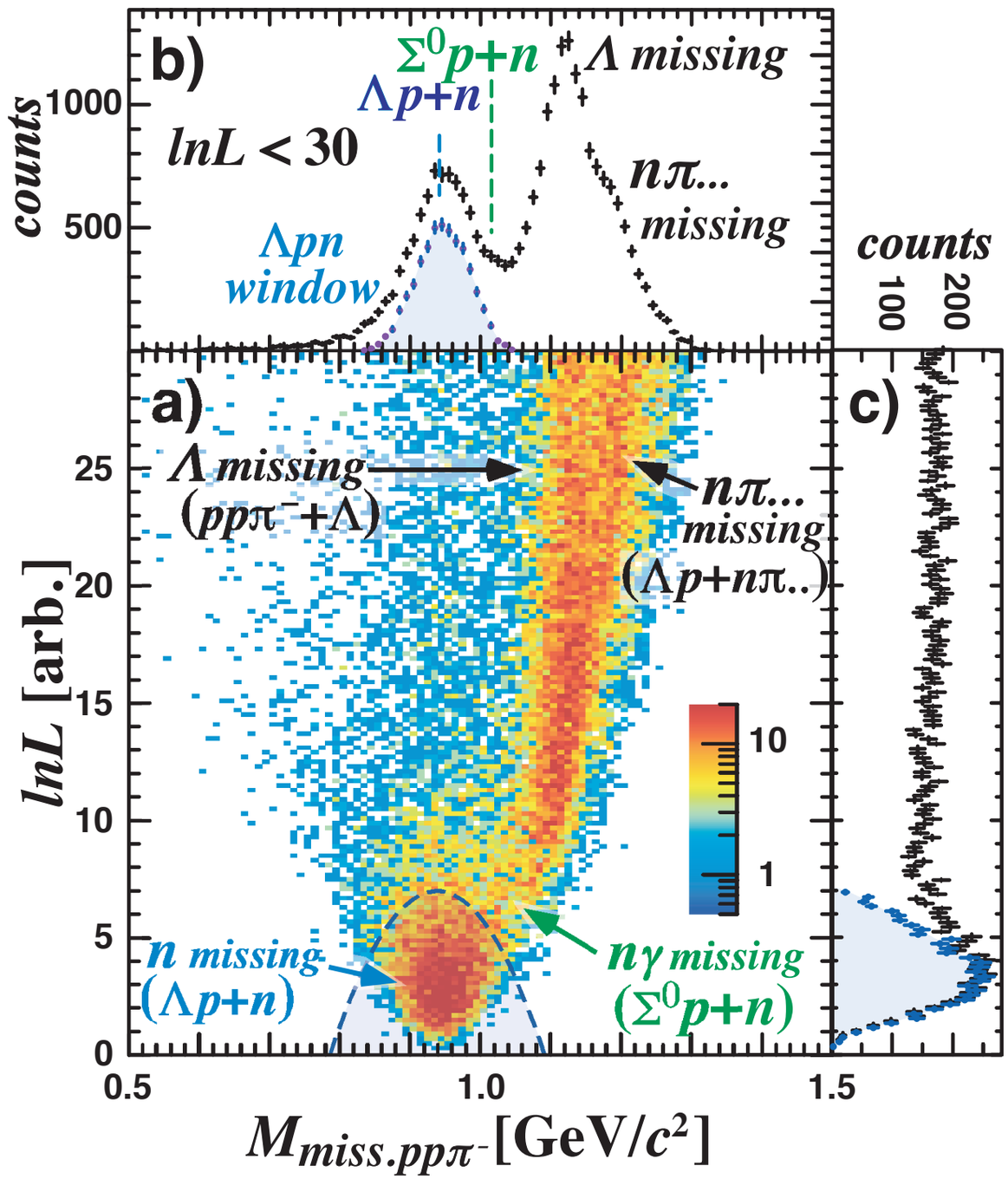
lnL has

DCA=0? K⁻ p vertex
K⁻ Λ vertex
p π⁻ vertex for Λ

K⁻ p vertex = K⁻ Λ vertex

$M_{inv.p\pi^-} = m_\Lambda$?

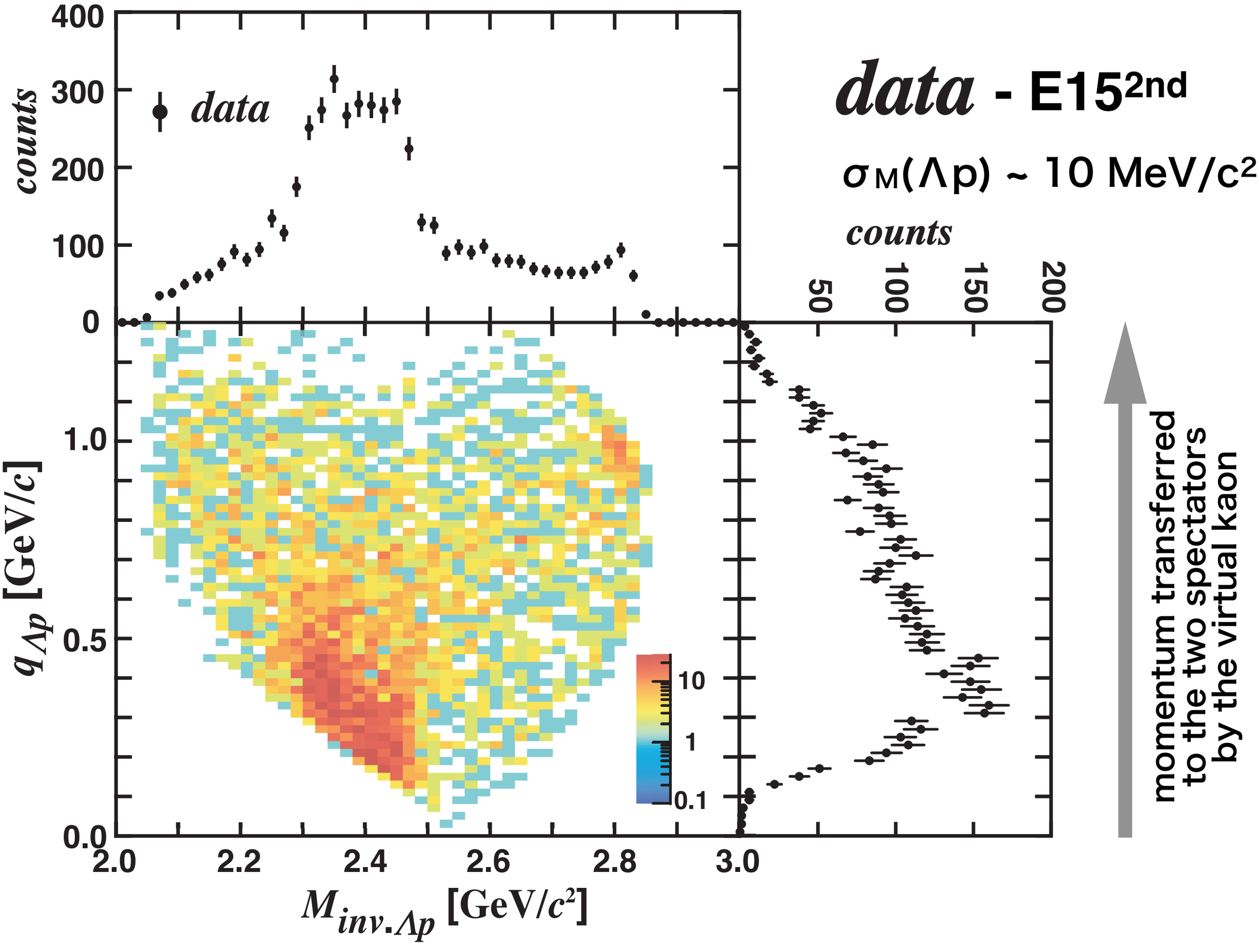
$M_{miss.pp\pi^-} = m_n$?



DCA: distance of closest approach of two trajectories

data - E15^{2nd}

$\sigma_M(\Lambda p) \sim 10$ MeV/c^2



data - E15 2nd

$\sigma_M(\Lambda p) \sim 10$ MeV/c^2

Kpp $QF_{\bar{K}A}$

Sekihara Oset Ramos

data

counts

400
300
200
100
0

50
100
150
200

counts

$q_{\Lambda p}$ [GeV/*c*]

1.0
0.5
0.0

10
1
0.1

2.0
2.2
2.4
2.6
2.8
3.0

$M_{inv.\Lambda p}$ [GeV/c^2]

momentum transferred
to the two spectators
by the virtual kaon

Sekihara Oset Ramos

Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166

We introduce three model functions to fit

"Kpp", $QF_{\bar{K}A}$, broad(BG)

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q) \times phys_X(M,q)$$

Sum of all

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$

$$\text{x} \sum_{counts} y_j \cdot phys_j(M_{inv.\Lambda p}, q)$$

M(Kpp)

data

K^-pp

$QF_{\bar{K}A}$

BG

all

$M_F(q)$

counts

$q_{\Lambda p}$ [GeV/c]

$M_{inv.\Lambda p}$ [GeV/c^2]

KN→KN, KNN→Λp

$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$

x $phys_{KE}(M,q)$

M(Kpp)

data

$QF_{\bar{K}A}$

counts

400
300
200
100
0

50
100
150
200

forward K
(or direct K)

$M_F(q)$

$QF_{\bar{K}A}$

backward K

10
1
0.1

$q_{\Lambda p}$ [GeV/*c*]

1.0
0.5
0.0

2.0
2.2
2.4
2.6
2.8
3.0

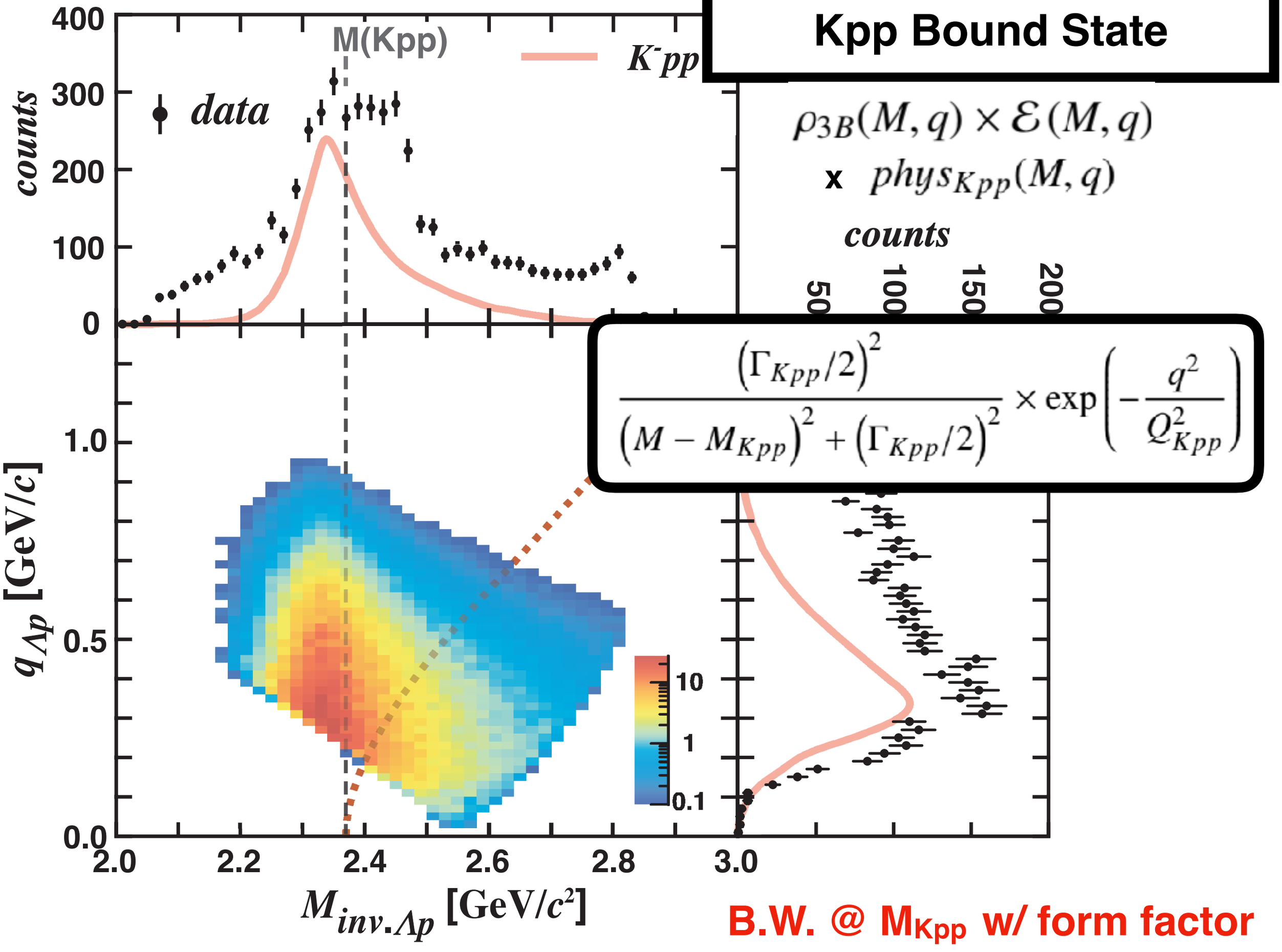
$M_{inv.\Lambda p}$ [GeV/c^2]

moving Gaussian with larger yields@ small & large *q*

Kpp Bound State

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$
$$\text{x} \quad phys_{Kpp}(M,q)$$

$$\frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q^2_{Kpp}}\right)$$



B.W. @ M_{Kpp} w/ form factor

broad BG

$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$

x $phys_X(M,q)$

M(Kpp)

data

BG

counts

$M_F(q)$

$q_{\Lambda p}$ [GeV/*c*]

$M_{inv.\Lambda p}$ [GeV/c^2]

cannot accommodate large yield @ lower *q*

Sum of all

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q)$$

$$\text{x} \sum_{counts} y_j \cdot phys_j(M_{inv.\Lambda p}, q)$$

M(Kpp)

data

K^-pp

$QF_{\bar{K}A}$

BG

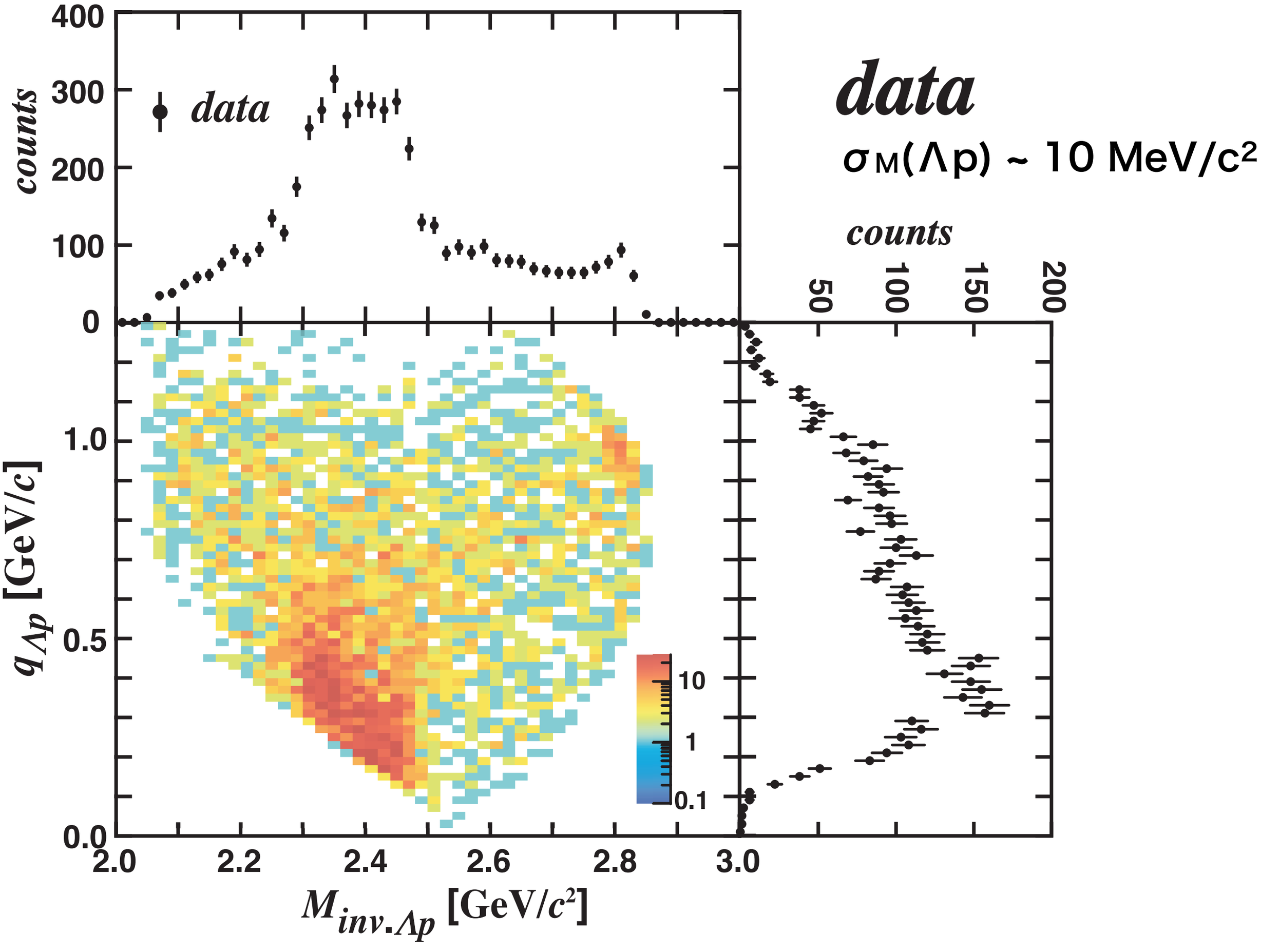
all

$M_F(q)$

counts

$q_{\Lambda p}$ [GeV/c]

$M_{inv.\Lambda p}$ [GeV/c^2]



data

$\sigma_M(\Lambda p) \sim 10$ MeV/c^2

data

focusing on "Kpp" dominant region 350 < q < 650 MeV/c

M(Kpp)

data

K^-pp

$QF_{\bar{K}A}$

BG

all

counts

$M_F(q)$

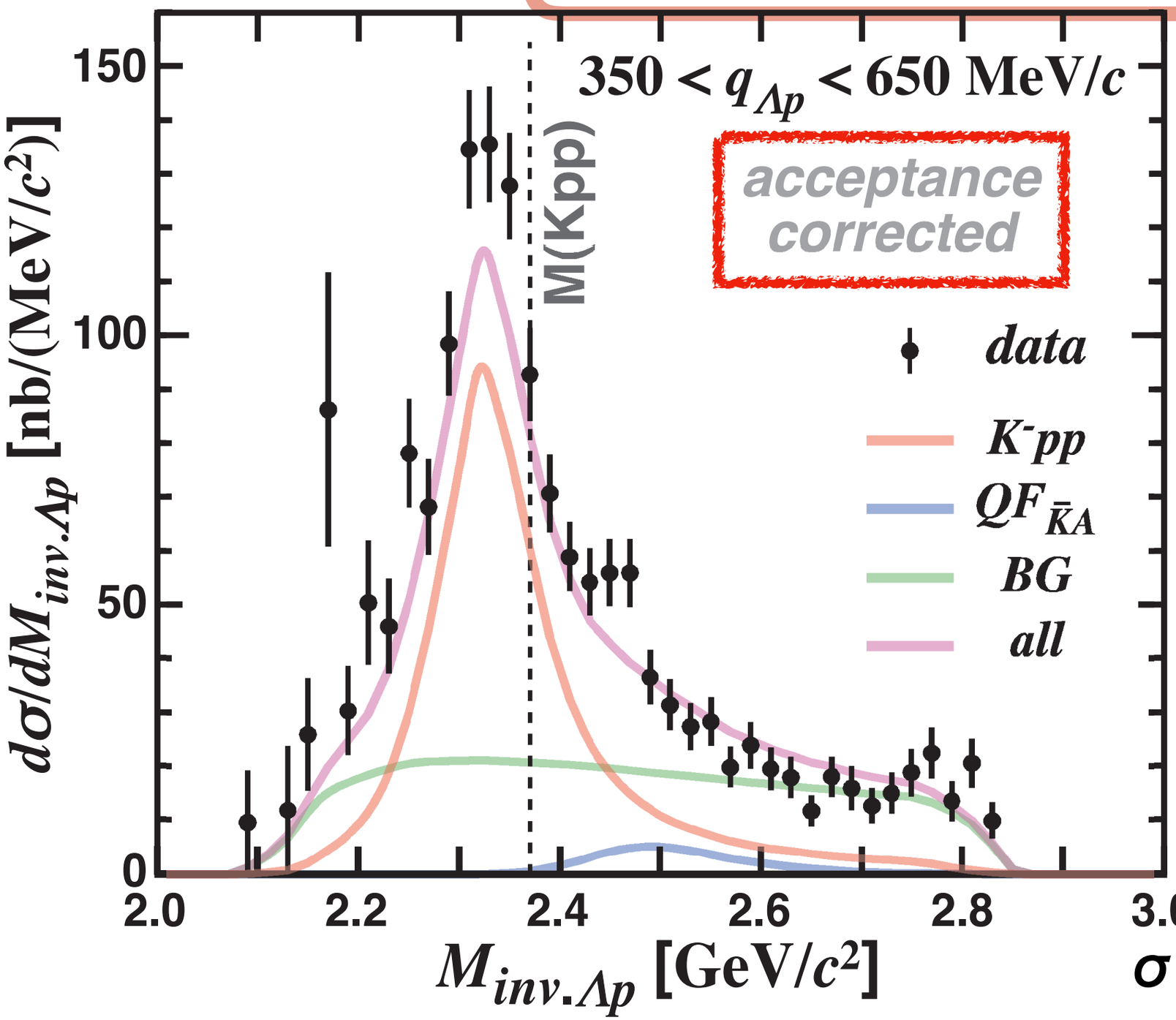
$q_{\Lambda p}$ [GeV/c]

$M_{inv.\Lambda p}$ [GeV/c^2]

QF-K escaping form region of interest @ higher *q*

$M_{inv.\Lambda p}$ q-selected $n_{mis.}$ + Λ p

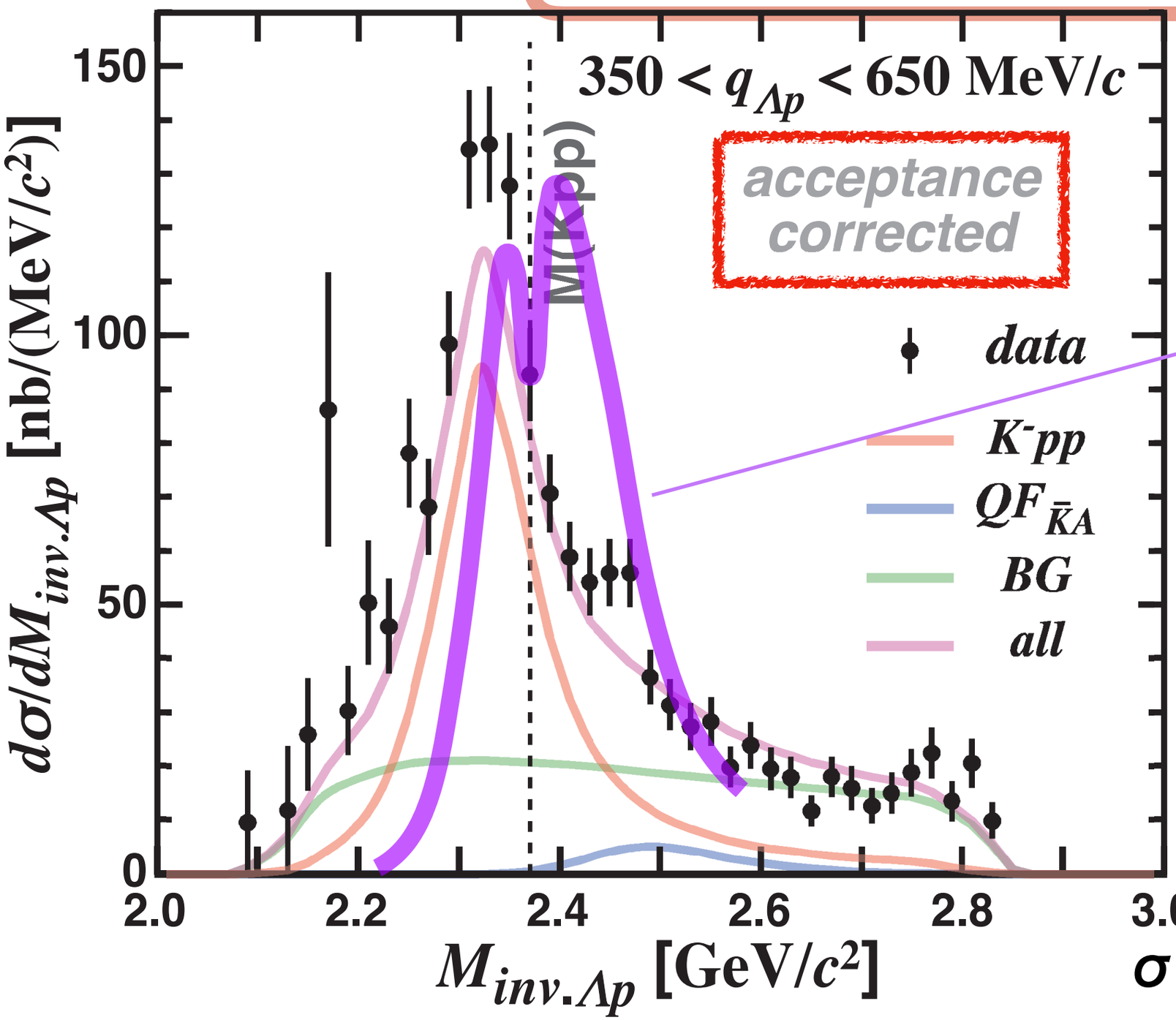
$$\rho_{3B}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$



$\sigma_M(\Lambda p) \sim 10$ MeV/c²

$M_{inv.\Lambda p}$ q-selected $n_{mis.}$ + Λ p

$$\rho_{3B}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$



$\sigma_M(\Lambda p) \sim 10$ MeV/c²

conclusion A:

Definitive peak observed

B_{Kpp} ~50 MeV, Γ_{Kpp} ~ 100 MeV, Q_{Kpp} ~ 400 MeV

arXiv:1805.12275

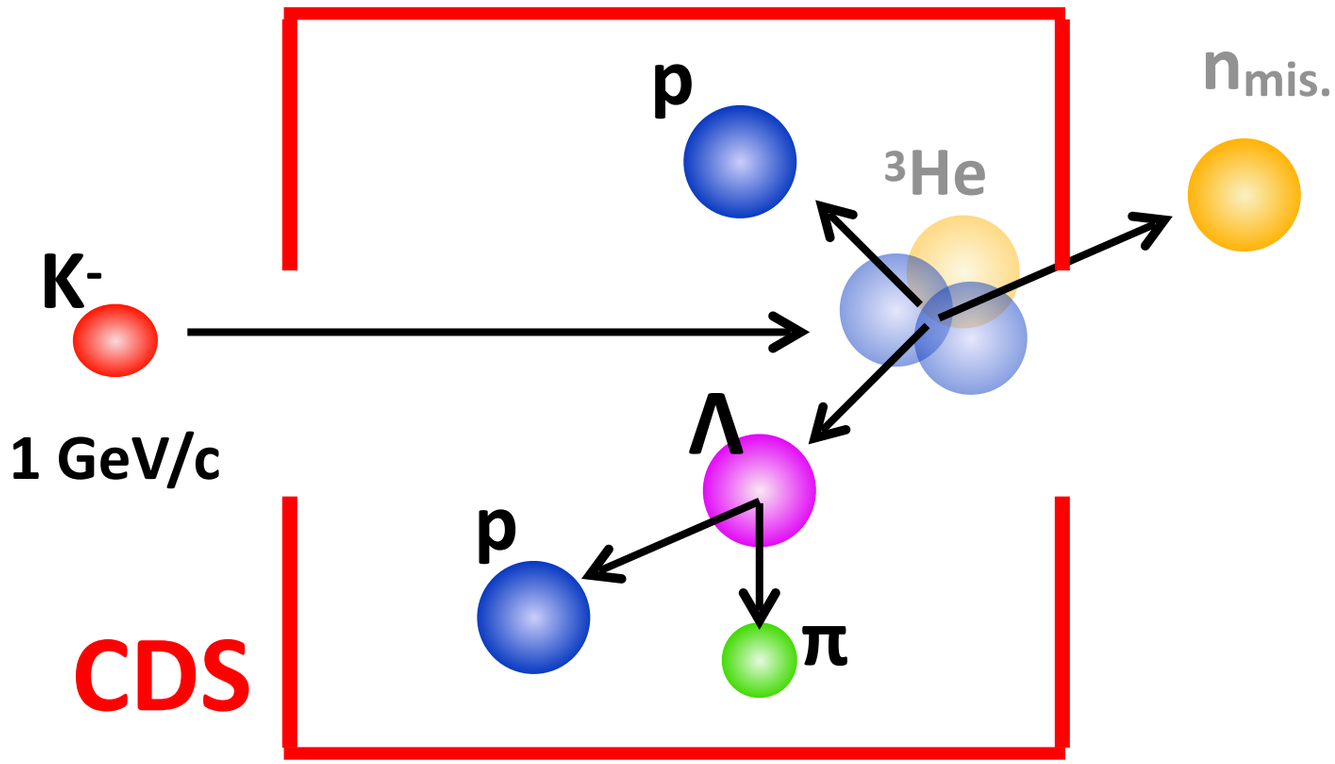
Three physical processes in Λpn final state

"Kpp", $QF_{\bar{K}A}$, broad(BG)

("Kpp" is consistent with S-wave)

Where is Λ*?

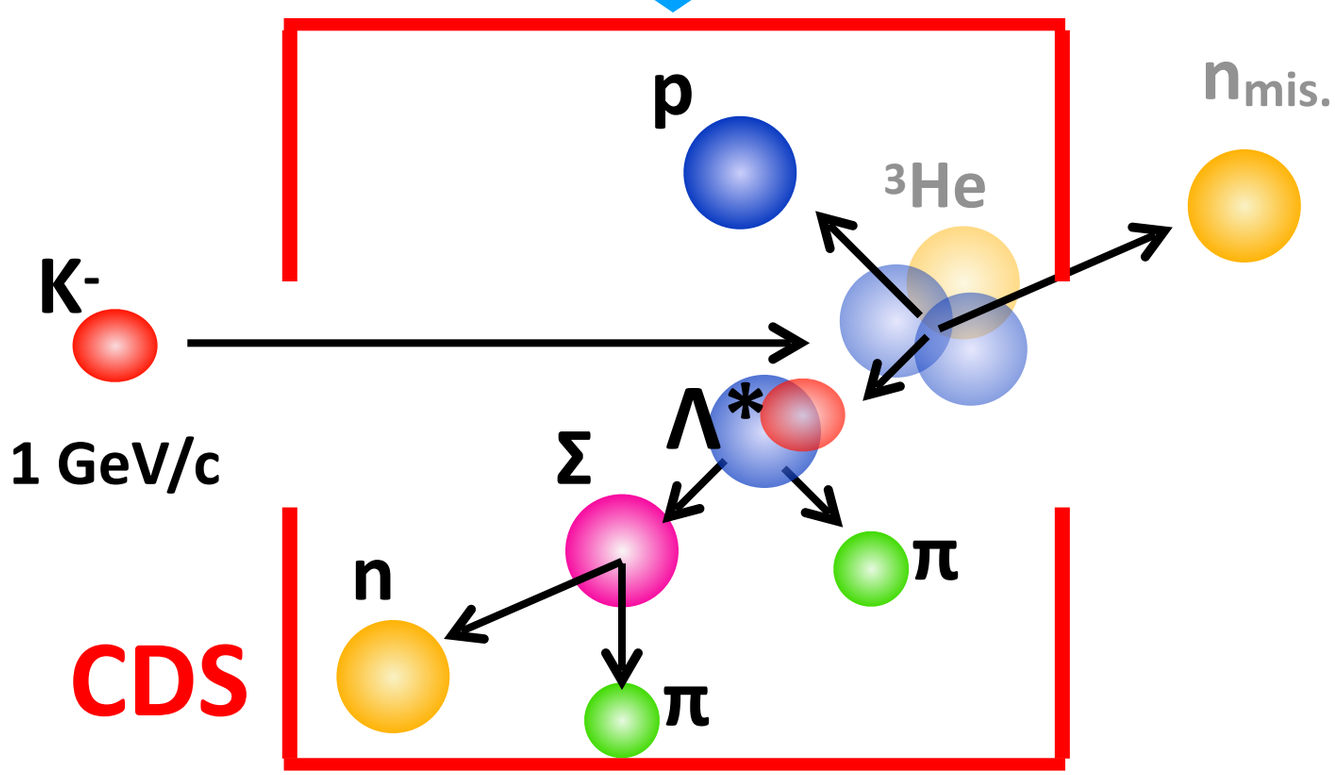
We started study assuming Λ(1405) = "K-p" bound state



if "K-pp" is formed

Λpn final state

arXiv:1805.12275



"K-p" must be formed

Λ*pn final state

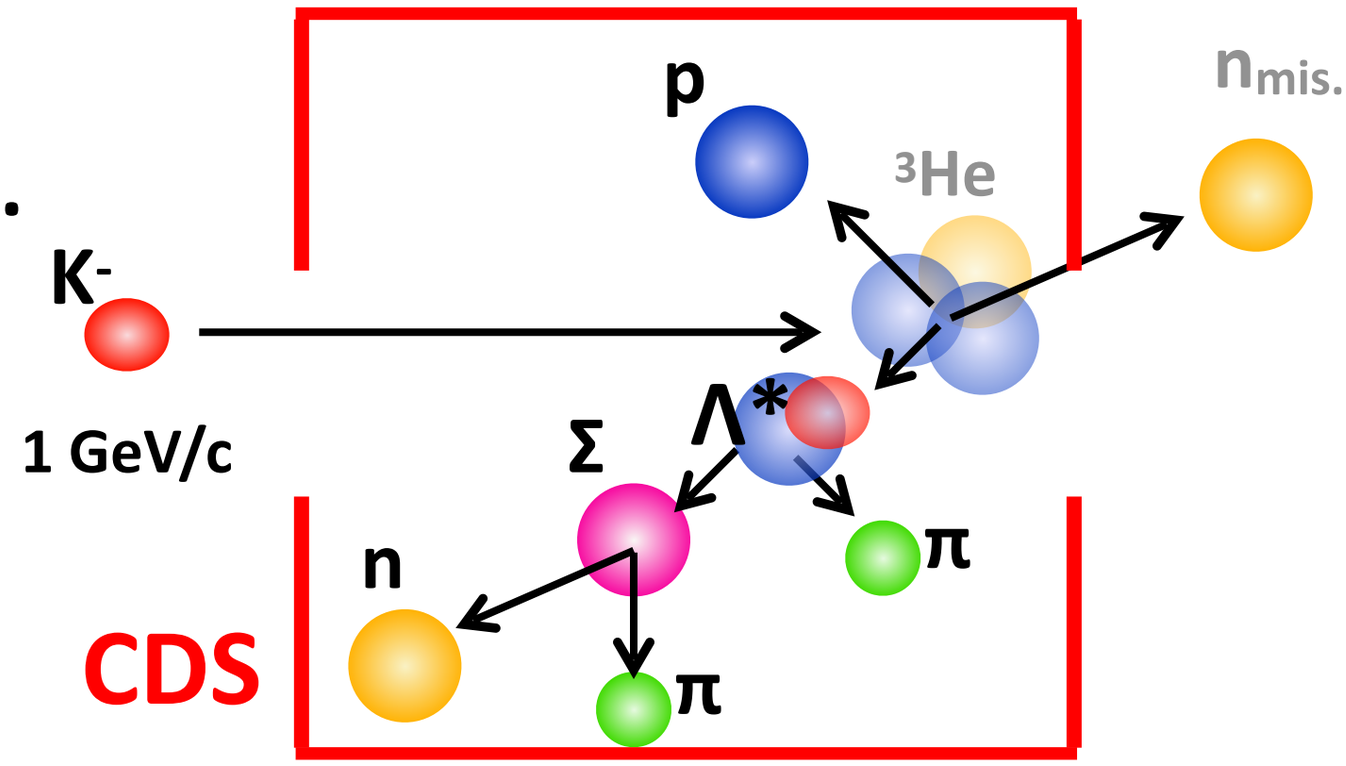
all preliminary

K^- $^3He \rightarrow \Lambda^* pn$ @ E15

- Exclusive measurement of
  $\pi^{\pm}\Sigma^{\mp}pn$ final state in K^-+^3He

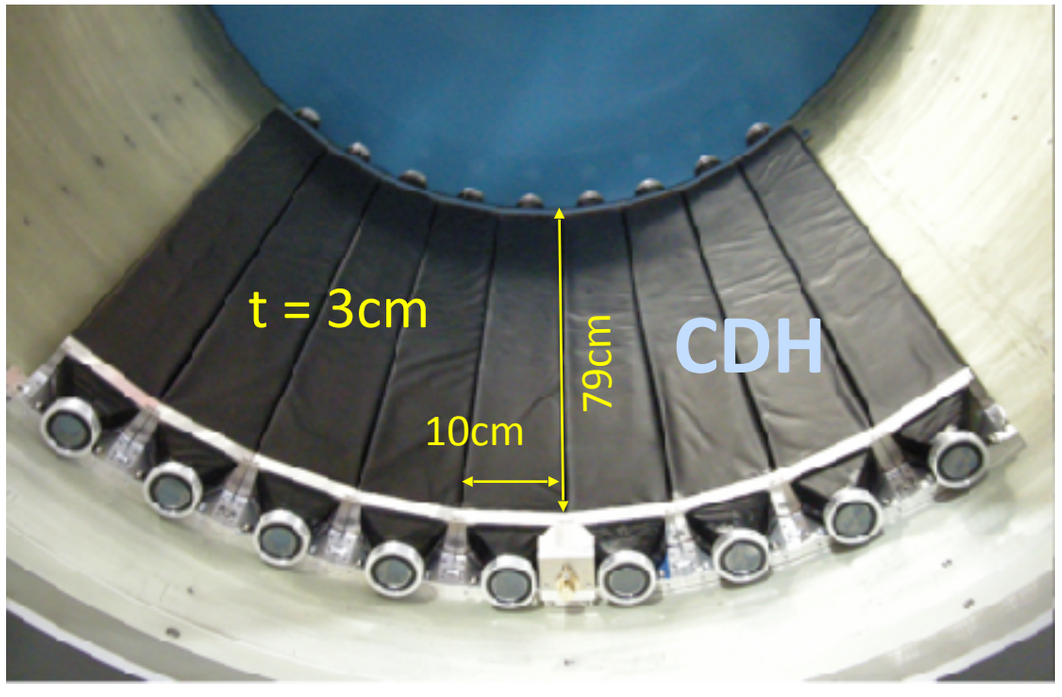
$(\pi^{\pm}\pi^{\mp}n\ p) + n_{mis.}$

4-hold coin. w/ n-missing



- **Experimental challenge**: neutron detection with plastic counter (t=3cm)

  n detection efficiency on CDH ~ 3%
  solid angle of CDH ~ 60%



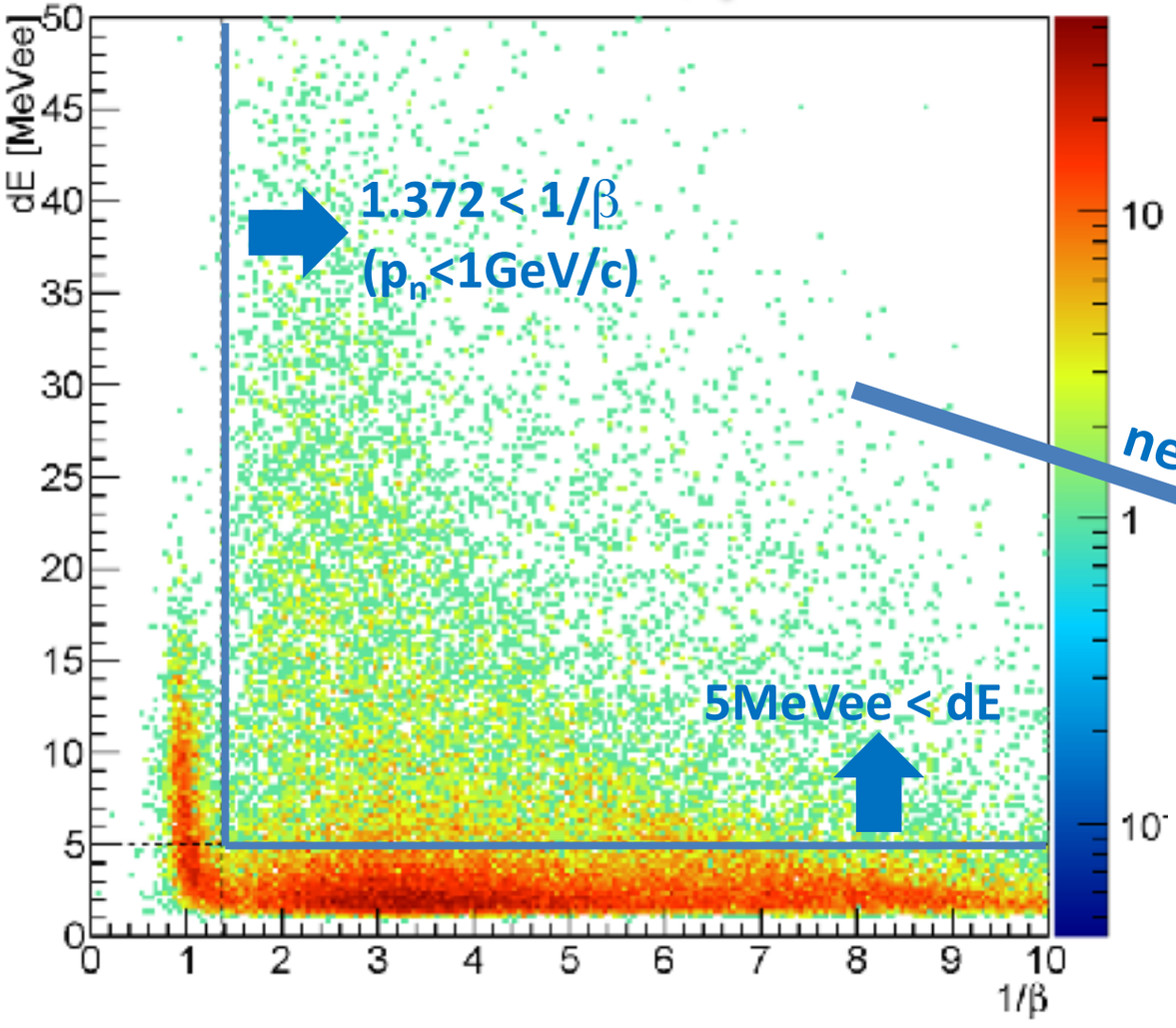
x 55 more difficult than Λpn

$(pp\pi^-) + n_{mis.}$ ***3-hold coin.***

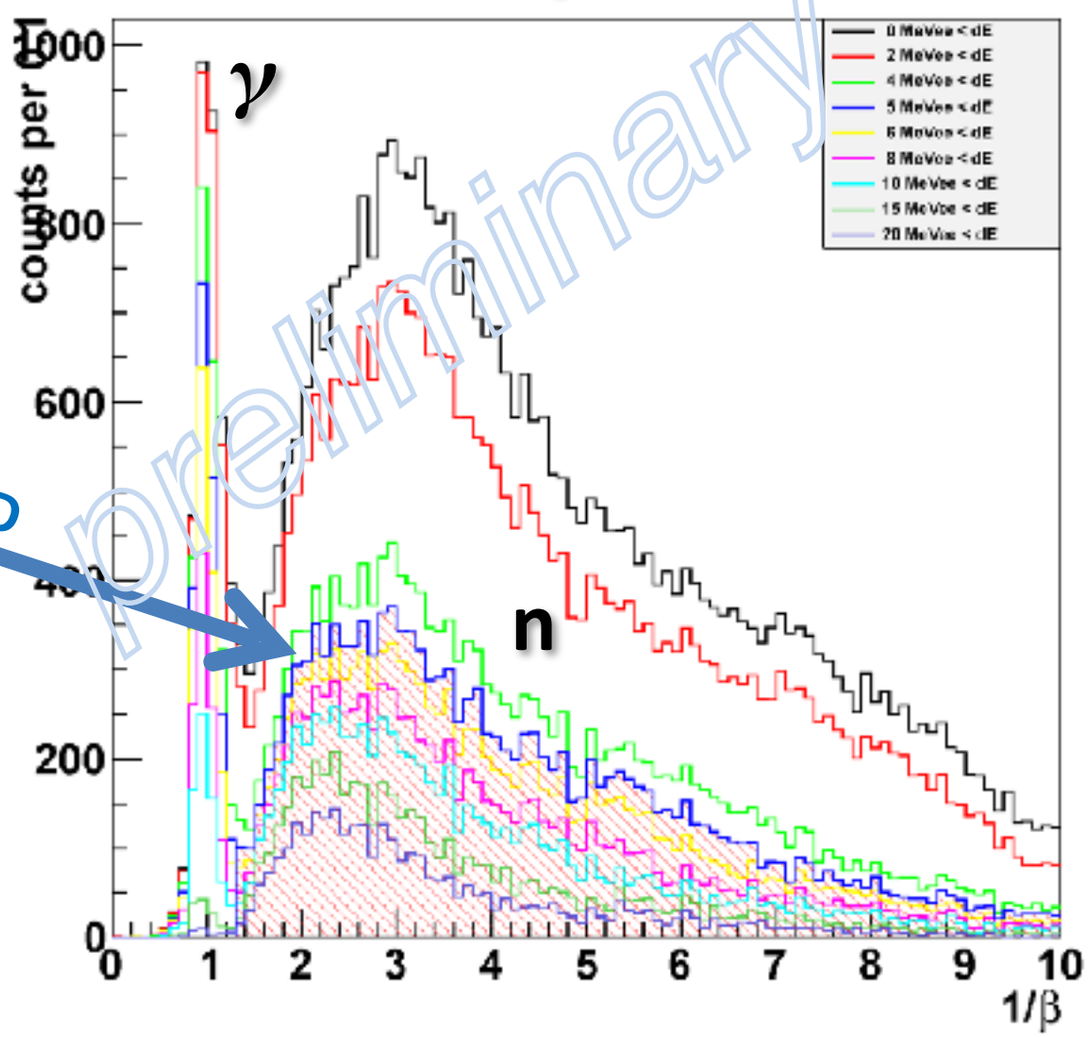
Neutron ID with CDH

- $\pi^+\pi^-$p events (3 tracks) in CDS with 4 CDH hits are selected
- a CDH hit with CDC-veto (outer-layer) is applied to identify the “neutral hit”

dE vs. 1/β



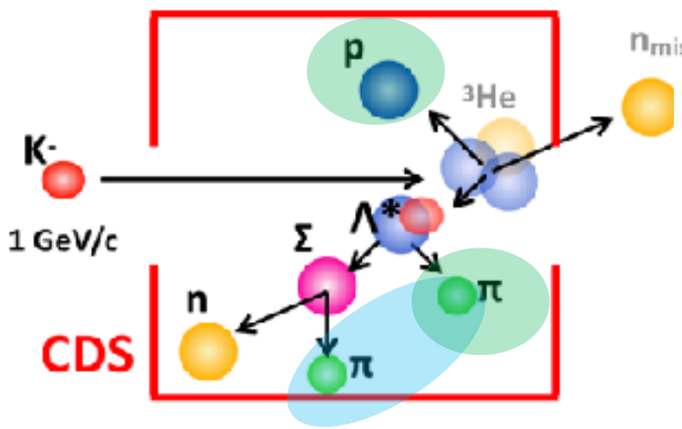
dE-cut dependence

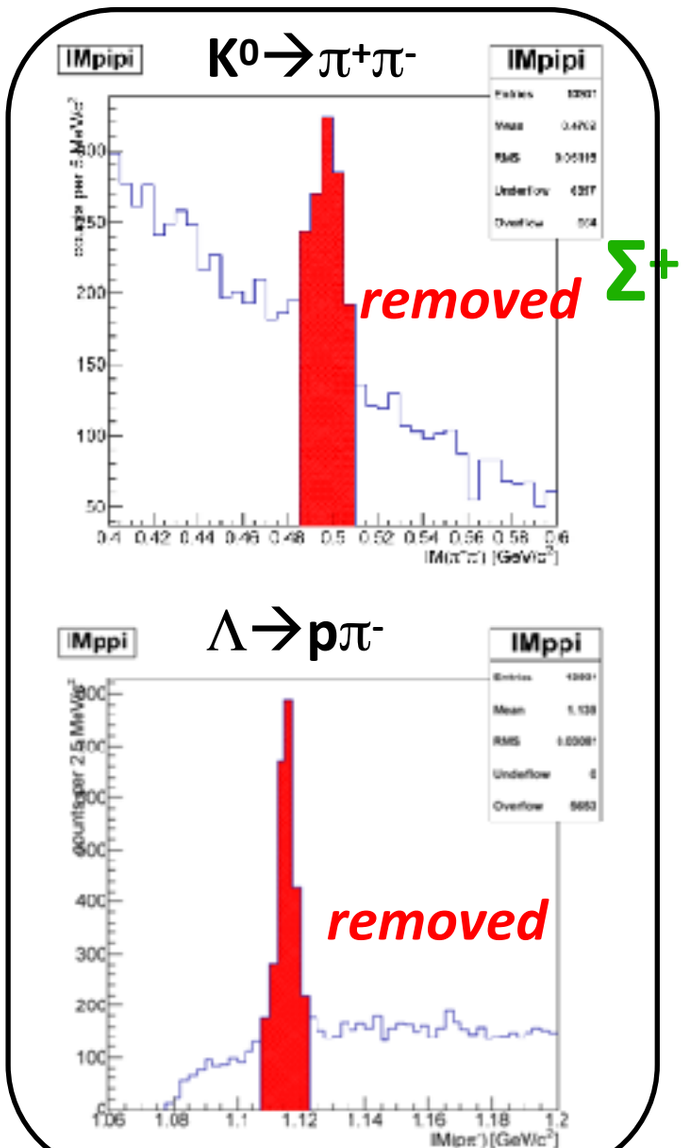


Neutron clearly identified by CDH

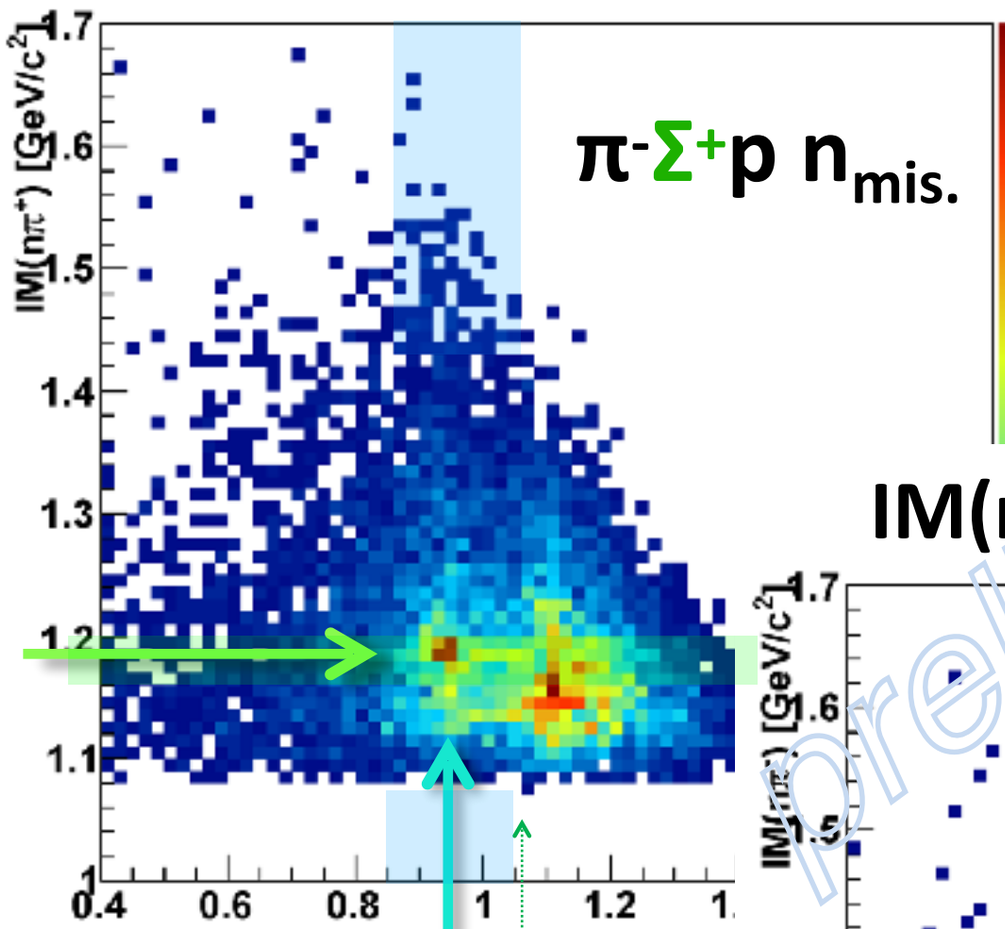
$\pi\pi p n \rightarrow \pi \Sigma p n$

remove unfavored events

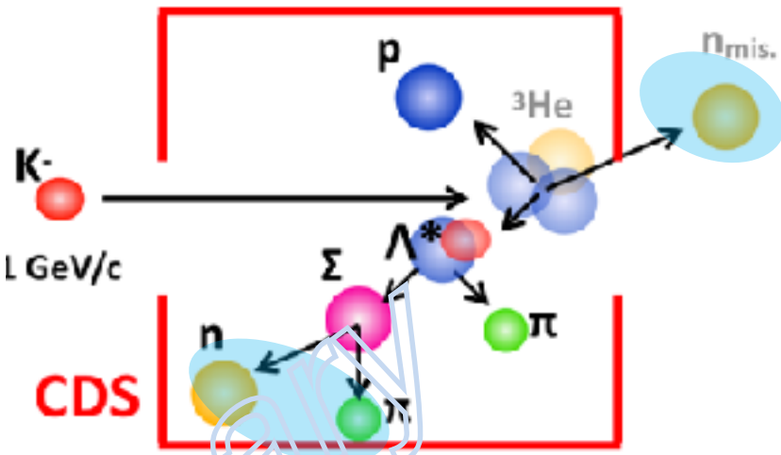




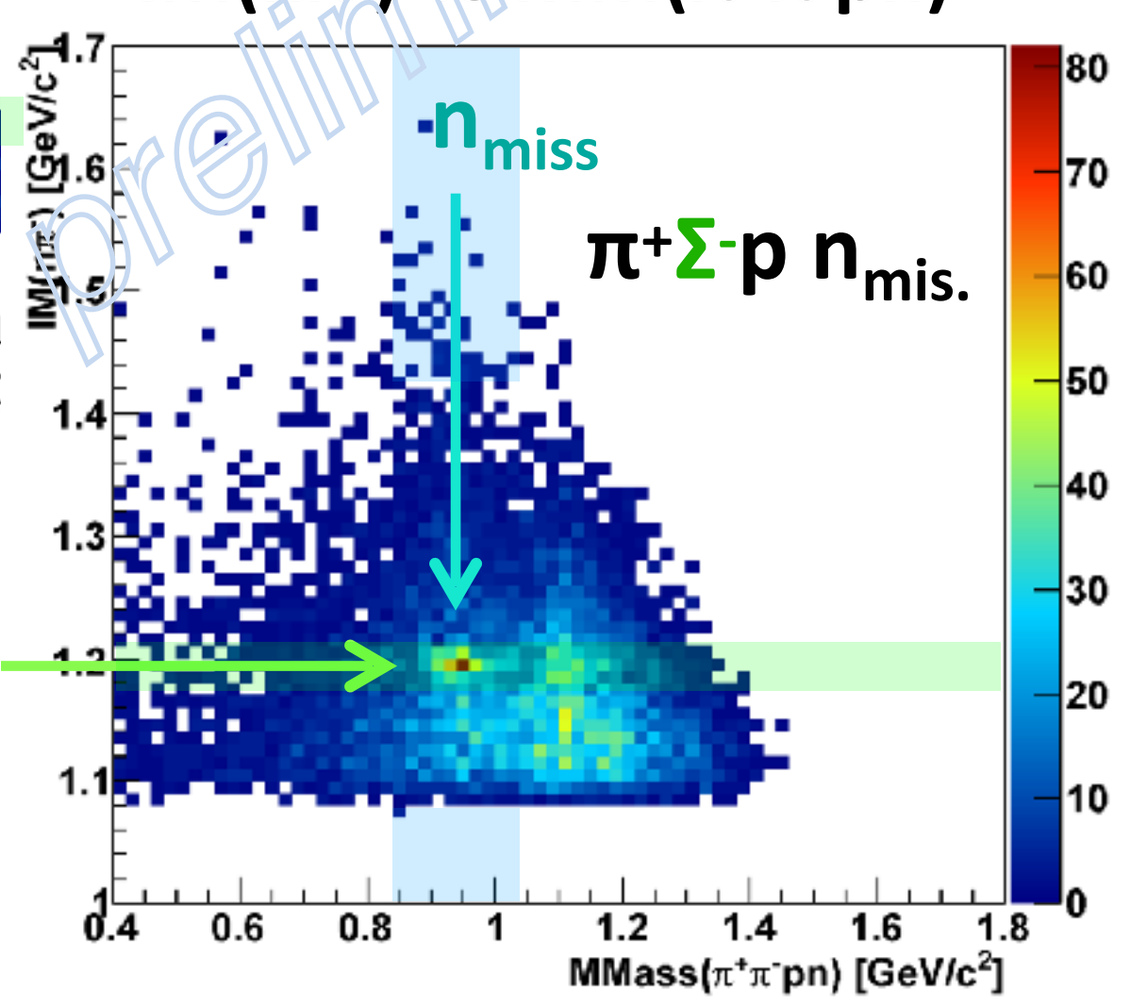
IM(nπ$^+$) vs MM(π$^+$π$^-$pn)



Σ identification



IM(nπ$^-$) vs MM(π$^+$π$^-$pn)



Λ*(πΣ)p*n* final state

Event Selection

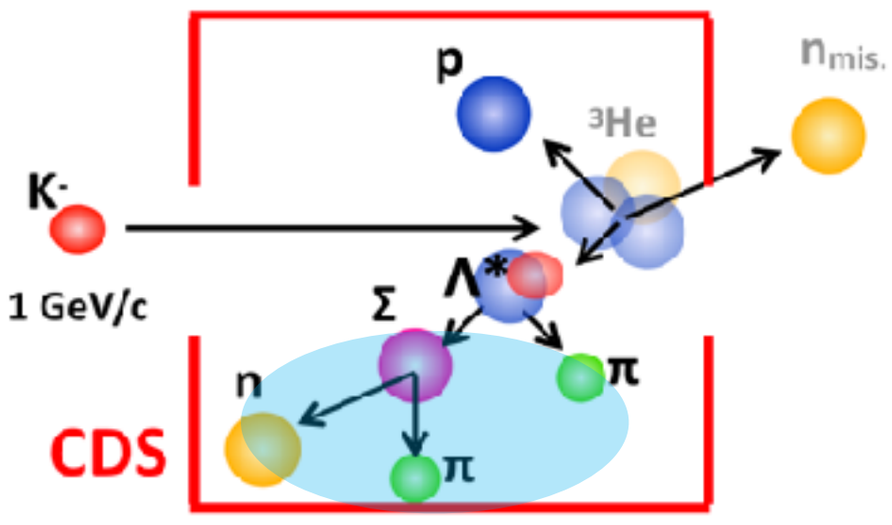
Missing n:

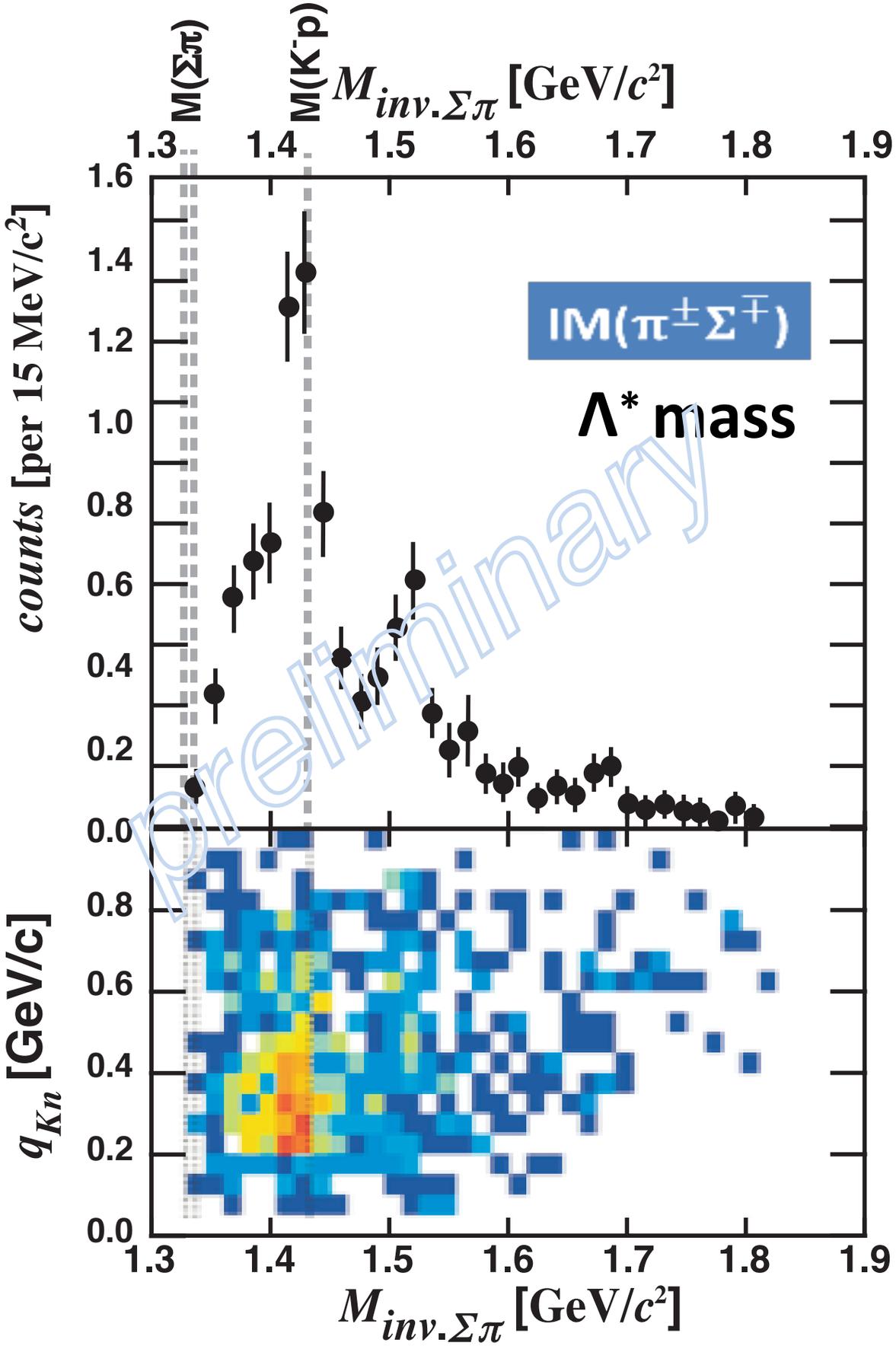
$0.85 < MM(\pi^+\pi^- pn) < 1.03$ GeV/c²

Σ mass:

$1.18 < IM(n\pi^-) < 1.20$ GeV/c² for Σ^-

$1.19 < IM(n\pi^+) < 1.21$ GeV/c² for Σ^+





Λ*(πΣ)p*n* final state

Event Selection

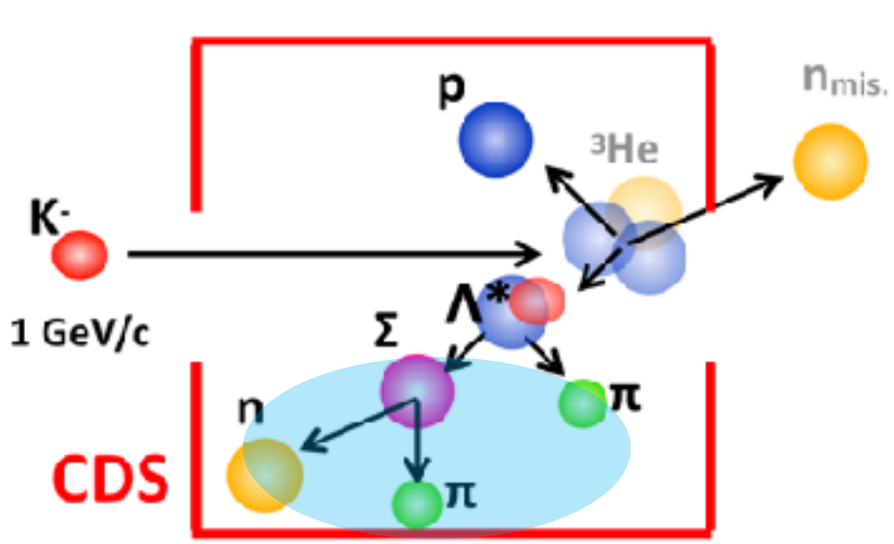
Missing n:

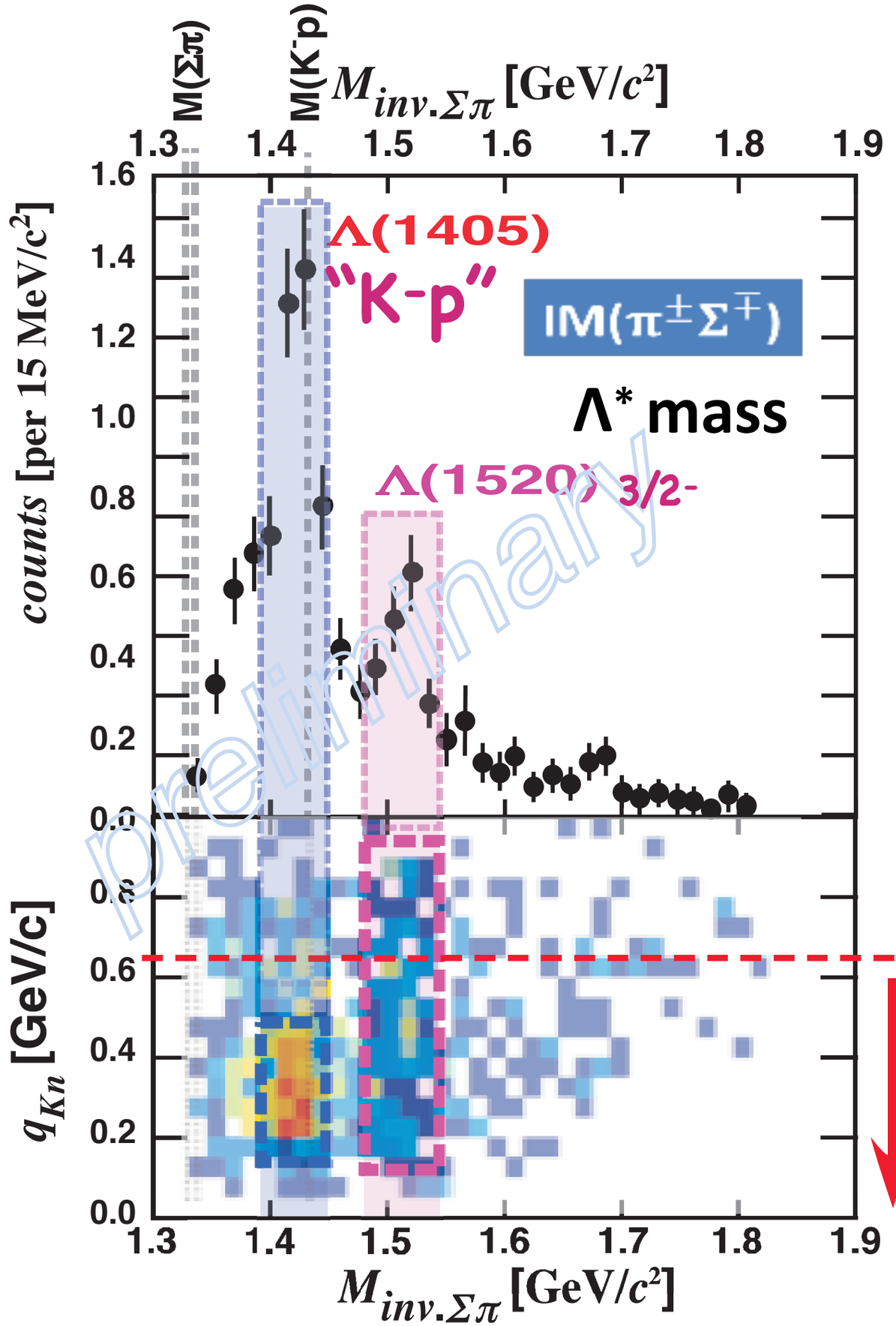
$0.85 < MM(\pi^+\pi^- pn) < 1.03$ GeV/c²

Σ mass:

$1.18 < IM(n\pi^-) < 1.20$ GeV/c² for Σ^-

$1.19 < IM(n\pi^+) < 1.21$ GeV/c² for Σ^+





"K⁻p" localized @ smaller q
in contrast to Λ(1520)

"K⁻p" = Λ(1405) / Λ(1520) = 3-quark baryon??

Y* Cross Section (q_{Kn}<0.65 GeV/c)

$\Lambda(1405)$

~ 130-140 μb

Flatté param.:

m_R ~ 1418 MeV/c

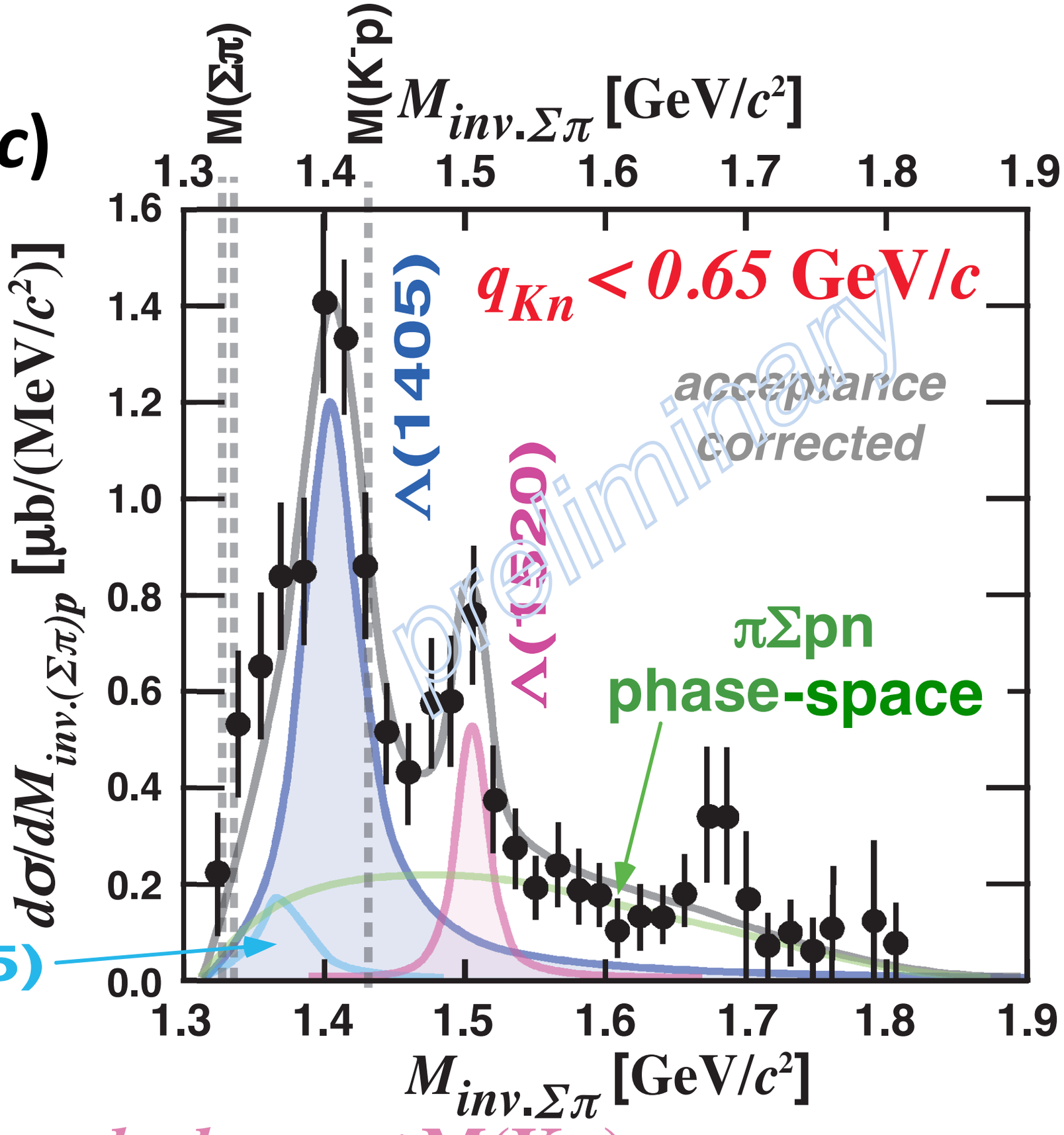
$g_{\pi\Sigma}$ ~ 1.9E-1

g_{KN} ~ 1.7E-2

~ 40-80 μb

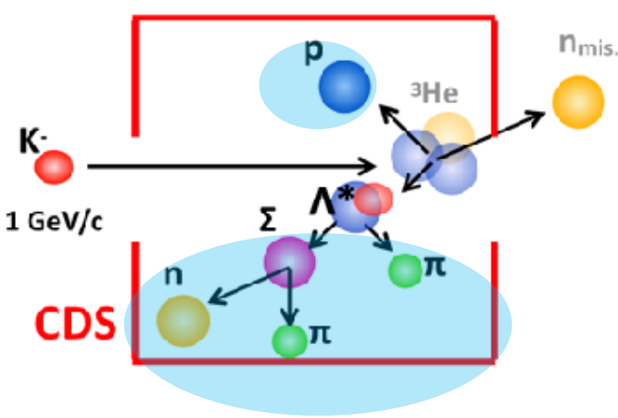
[evaluated from $\Sigma^+(1385)\rightarrow\pi^+\Lambda$ measurement]

$\Sigma^0(1385)$

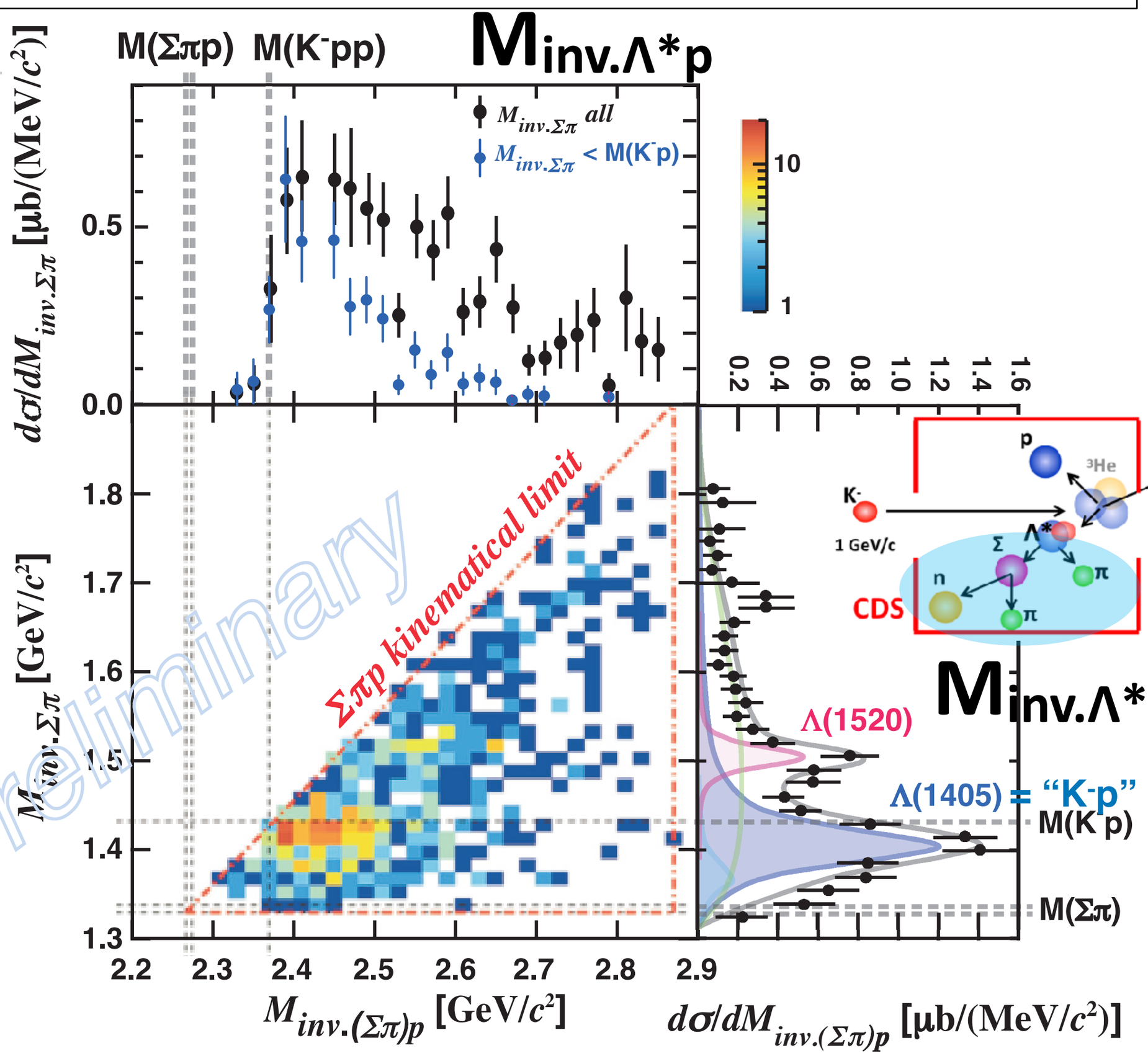


Λ(1405) strength sharply drops at M(Kp)

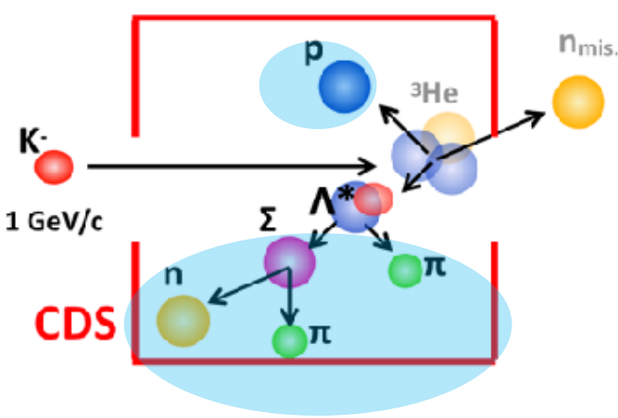
$M_{inv.\Lambda^*p}$ - *vs* - $M_{inv.\Lambda^*}$ ($\Lambda^* \rightarrow \pi\Sigma$)



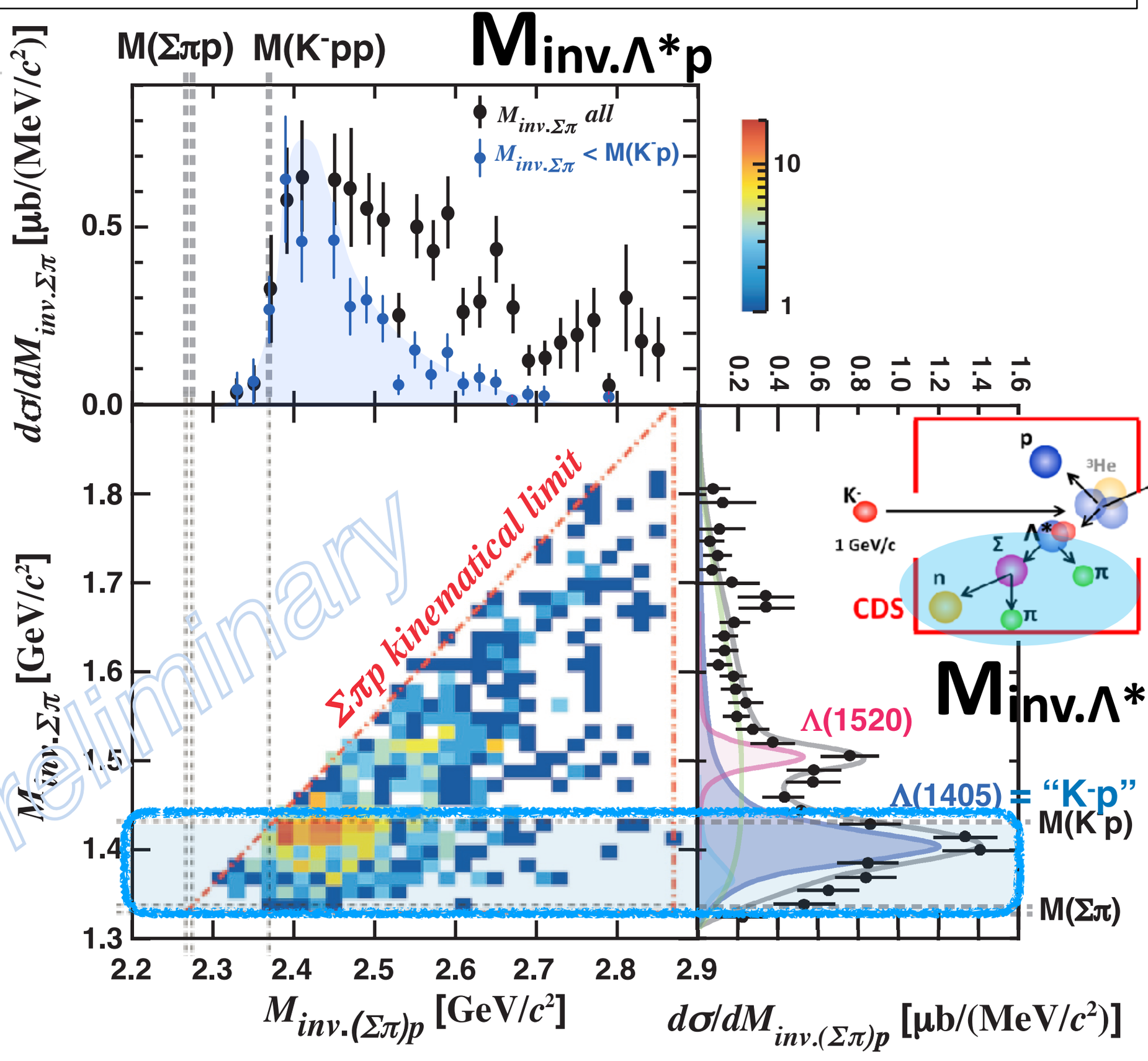
$M_{inv.\Lambda^*p}$



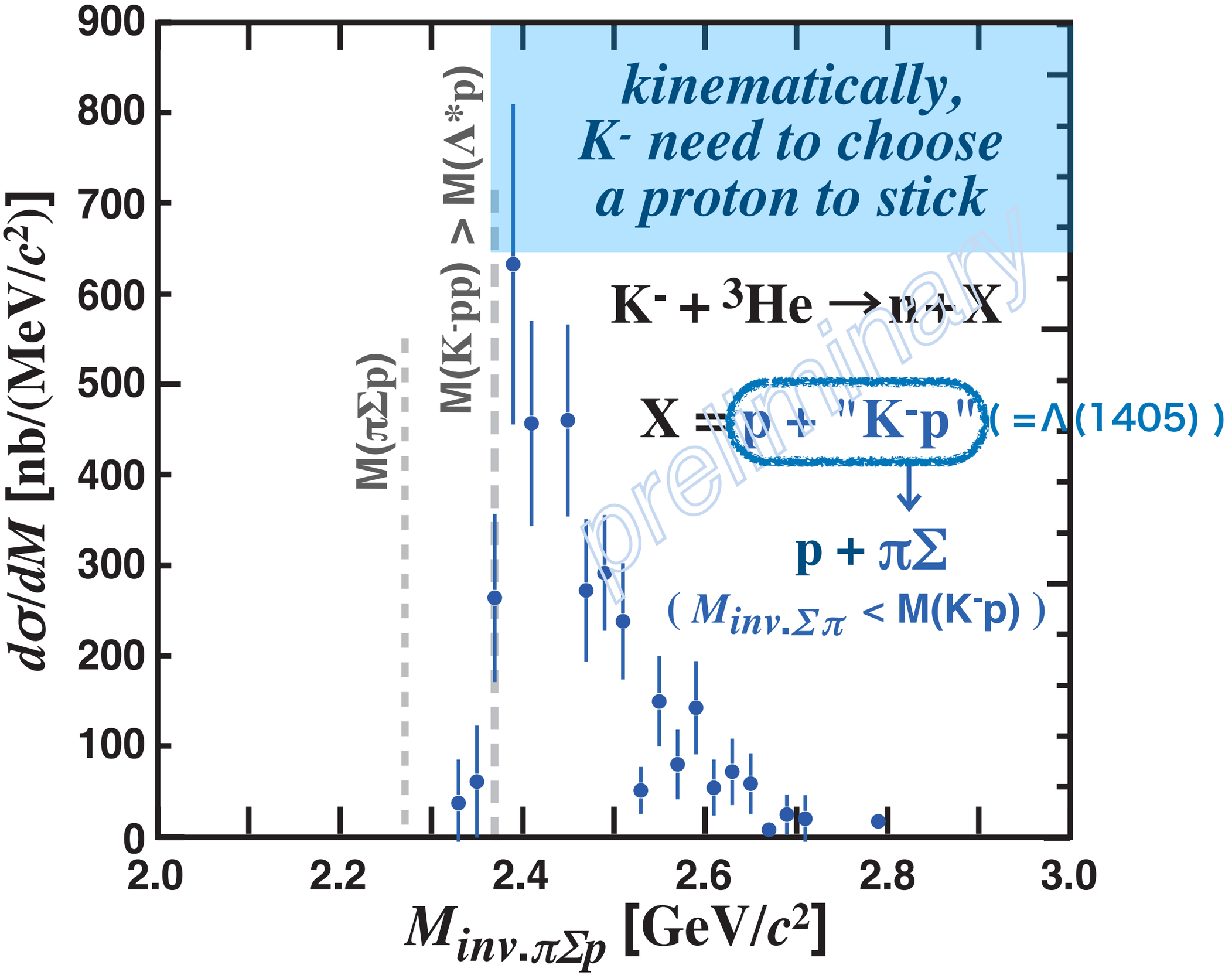
$M_{inv.\Lambda^*p}$ - *vs* - $M_{inv.\Lambda^*}$ ($\Lambda^* \rightarrow \pi\Sigma$)



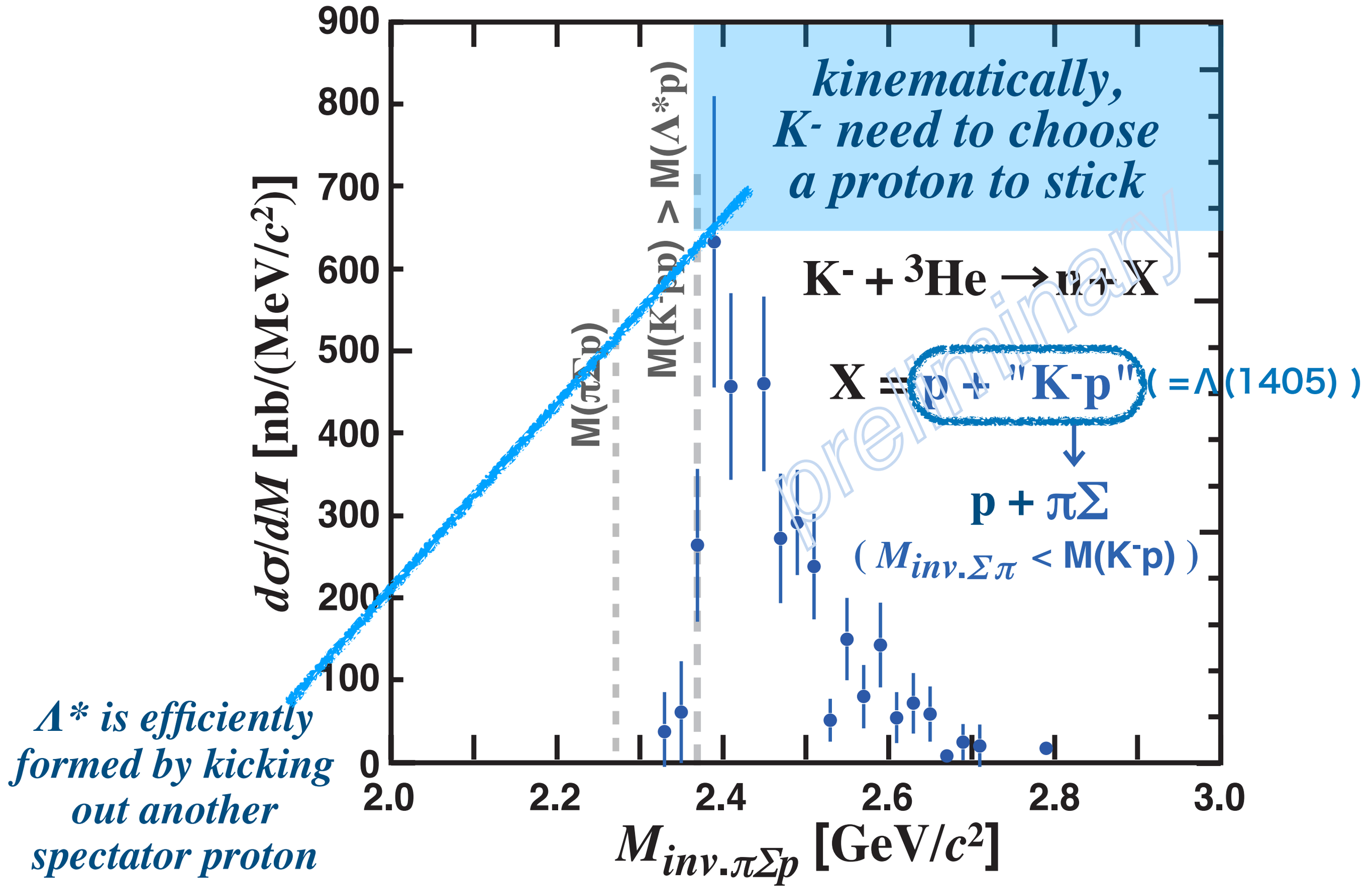
$M_{inv.\Lambda^*p}$



Λ* + p = "K⁻p" + p

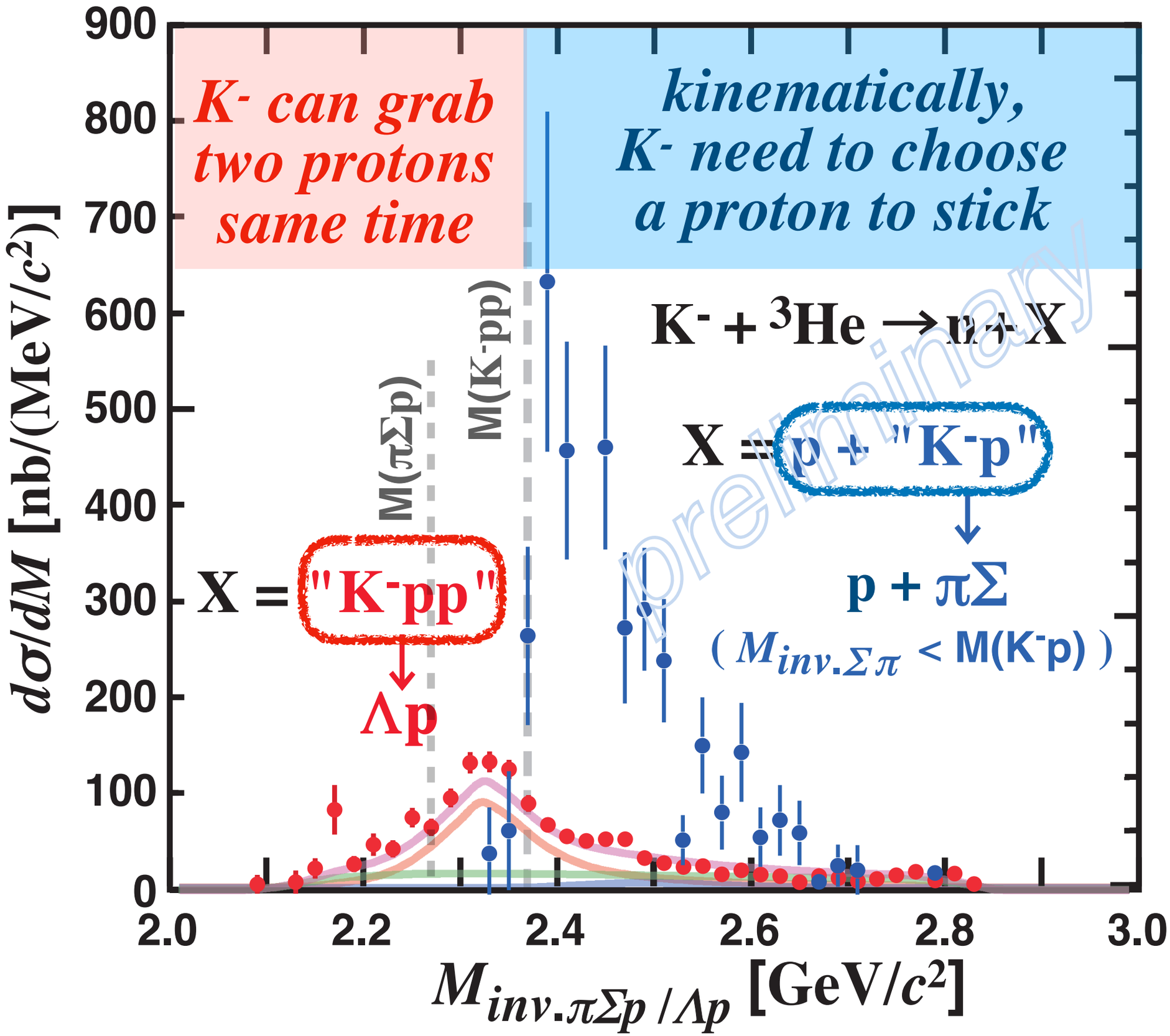

kinematically,
K⁻ need to choose
a proton to stick
M(K⁻pp) > M(Λ*p)
M(πΣp)
K⁻ + ³He → n + X
X = p + "K⁻p" (=Λ(1405))
p + πΣ
(M_inv.Σπ < M(K⁻p))
preliminary
dσ/dM [nb/(MeV/c²)]
M_inv.πΣp [GeV/c²]
0
100
200
300
400
500
600
700
800
900
2.0
2.2
2.4
2.6
2.8
3.0

Λ* + p = "K⁻p" + p

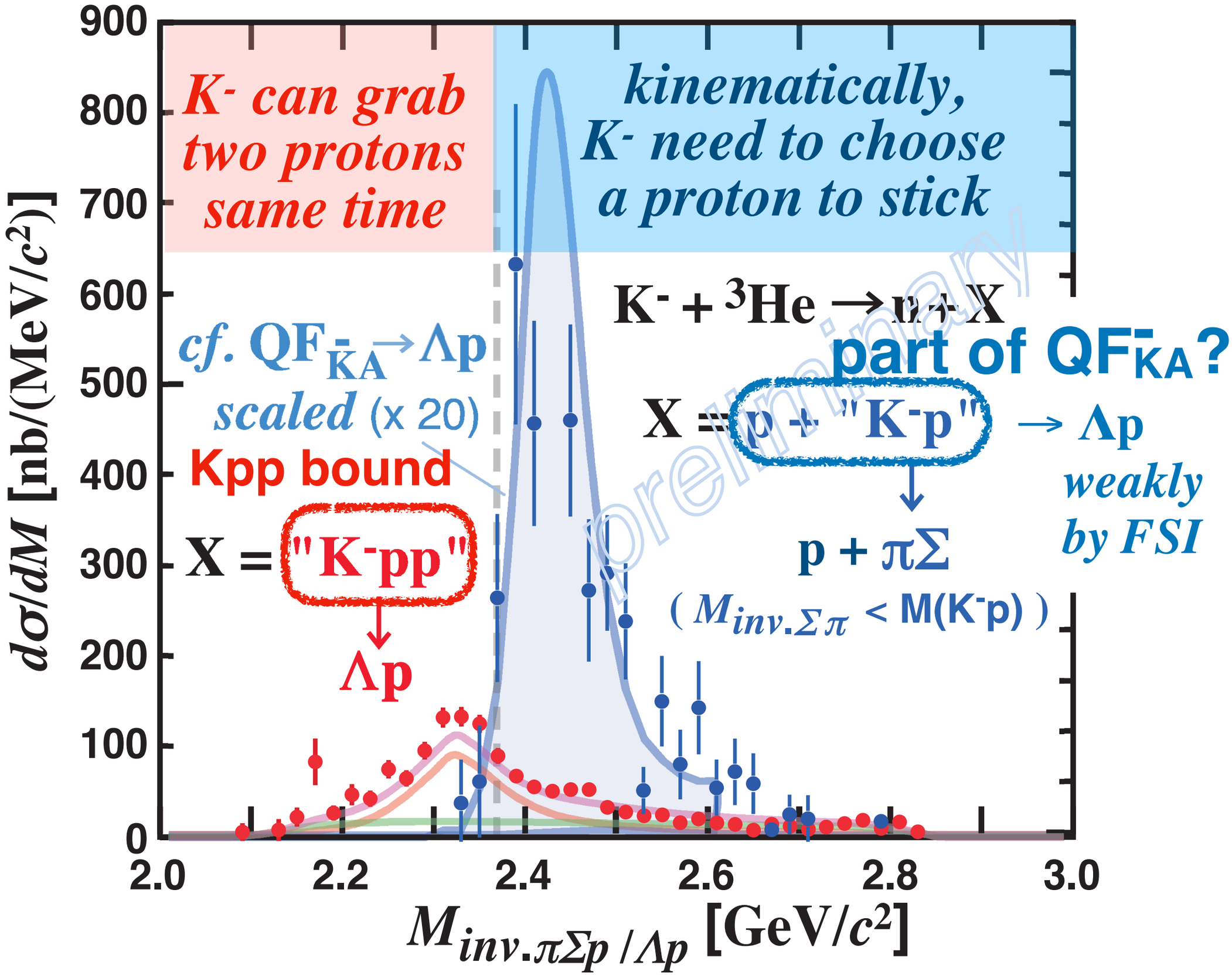


Λ is efficiently formed by kicking out another spectator proton*

"K⁻pp" → Λp - *vs* - "K⁻p" + p → πΣ + p



"K⁻pp" - *vs* - $QF_{\bar{K}A}$



conclusion B:

"Kp" (=Λ*) formation observed

with sharp drop at M(Kp)

reaction summary:

$$n + \text{“}K^- p\text{”} + p \rightarrow \Lambda^* \rightarrow n + \Lambda + p \quad \textit{weakly by FSI}$$

$$n + (\pi + \Sigma)^0 + p$$

$$K^- + {}^3He \rightarrow \text{----------} M(Kpp)$$

$$n + \text{“}K^- pp\text{”} \rightarrow n + \Lambda + p$$

virtual "K-" energy controls the reaction branch

"Kpp" seems more like 'Kpp' rather than 'Λ*p'

consistent picture w/ "K-p" & "K-pp"

HYP2018

June 24 - 29, 2018

yet another conclusion

We wish to open a new era on K meson nuclear bound state

Help us if you can!

The E15 Collaborations

S. Ajimura[1], H. Asano[2], G. Beer[3], C. Berucci[4], H. Bhang[5], M. Bragadireanu[6], P. Buehler[4], L. Busso[7,8], M. Cargnelli[4], S. Choi[5], C. Curceanu[9], S. Enomoto[10], H. Fujioka[11], Y. Fujiwara[12], T. Fukuda[13], C. Guaraldo[9], T. Hashimoto[14], R. S. Hayano[12], T. Hiraiwa[1], M. Iio[10], M. Iliescu[9], K. Inoue[1], Y. Ishiguro[15], T. Ishikawa[12], S. Ishimoto[10], K. Itahashi[2], M. Iwasaki[2,11],* K. Kanno[12], K. Kato[15], Y. Kato[2], S. Kawasaki[1], P. Kienle[16],† H. Kou[11], Y. Ma[2], J. Marton[4], Y. Matsuda[12], Y. Mizoi[13], O. Morra[7], T. Nagae[15], H. Noumi[1], H. Ohnishi[17,2], S. Okada[2], H. Outa[2], K. Piscicchia[9], Y. Sada[1], A. Sakaguchi[1], F. Sakuma[2],‡ M. Sato[10], A. Scordo[9], M. Sekimoto[10], H. Shi[9], K. Shirotori[1], D. Sirghi[9,6], F. Sirghi[9,6], K. Suzuki[4], S. Suzuki[10], T. Suzuki[12], K. Tanida[14], H. Tatsuno[18], M. Tokuda[11], D. Tomono[1], A. Toyoda[10], K. Tsukada[17], O. Vazquez Doce[9,16], E. Widmann[4], T. Yamaga[2,1],§ T. Yamazaki[12,2], Q. Zhang[2], and J. Zmeskal[4]

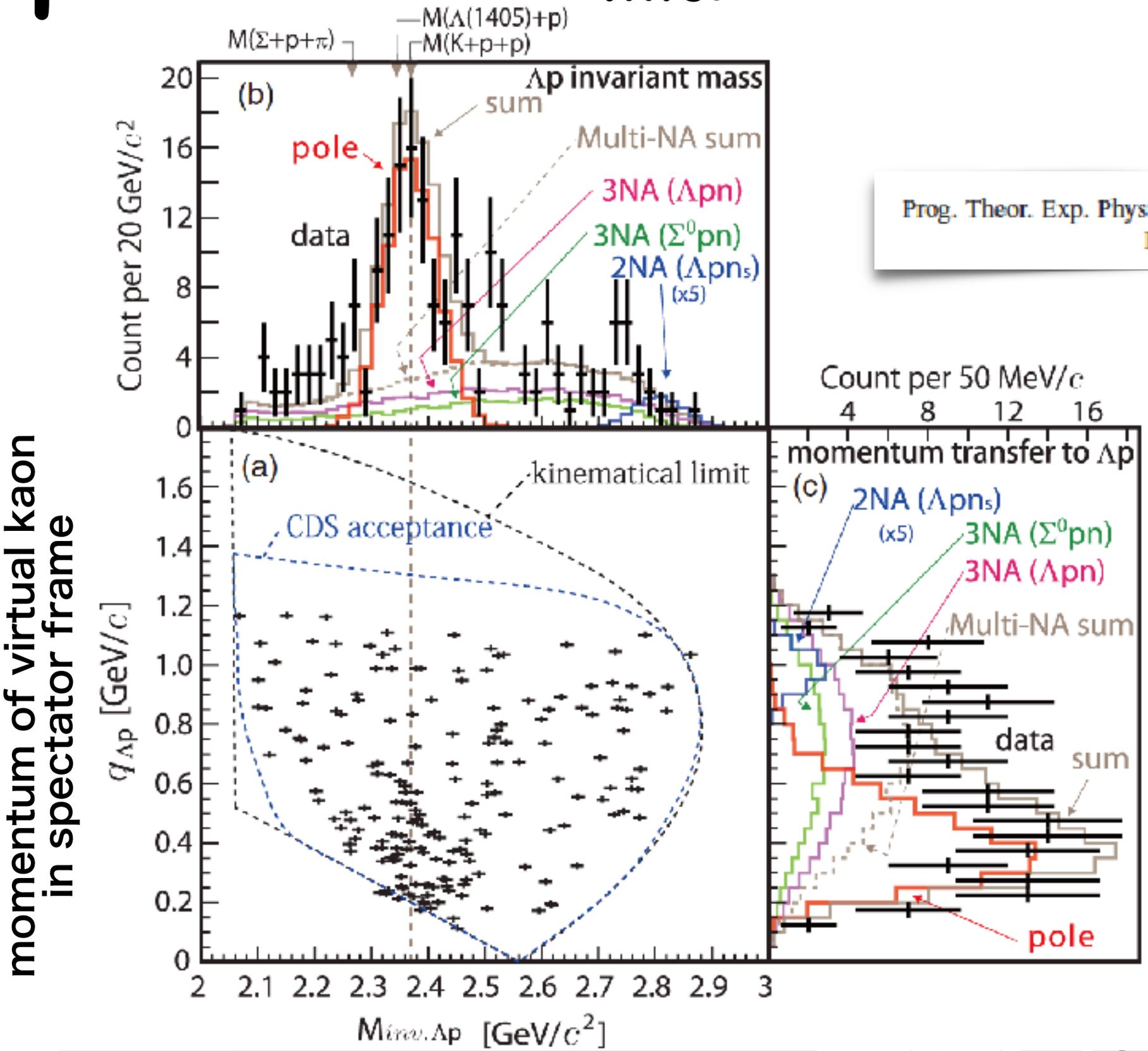
[1] *Osaka University, Osaka, 567-0047, Japan*
[2] *RIKEN, Wako, 351-0198, Japan*
[3] *University of Victoria, Victoria BC V8W 3P6, Canada*
[4] *Stefan-Meyer-Institut für subatomare Physik, A-1090 Vienna, Austria*
[5] *Seoul National University, Seoul, 151-742, South Korea*
[6] *National Institute of Physics and Nuclear Engineering - IFIN HH, Bucharest - Magurele, Romania*
[7] *INFN Sezione di Torino, 10125 Torino, Italy*
[8] *Universita' di Torino, Torino, Italy*
[9] *Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy*
[10] *High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan*
[11] *Tokyo Institute of Technology, Tokyo, 152-8551, Japan*
[12] *The University of Tokyo, Tokyo, 113-0033, Japan*
[13] *Osaka Electro-Communication University, Osaka, 572-8530, Japan*
[14] *Japan Atomic Energy Agency, Ibaraki 319-1195, Japan*
[15] *Kyoto University, Kyoto, 606-8502, Japan*
[16] *Technische Universität München, D-85748, Garching, Germany*
[17] *Tohoku University, Sendai, 982-0826, Japan and*
[18] *Lund University, Lund, 221 00, Sweden*

(J-PARC E15 Collaboration)

RIKEN Nishina Center, RIKEN, Wako, 351-0198, Japan
Laboratori Nazionali di Frascati dell' INFN, I-00044 Frascati, Italy
Department of Physics and Astronomy, University of Victoria, Victoria BC V8W 3P6, Canada
Department of Physics, Seoul National University, Seoul, 151-742, South Korea
National Institute of Physics and Nuclear Engineering - IFIN HH, Romania
Stefan-Meyer-Institut fu¨r subatomare Physik, A-1090 Vienna, Austria
INFN Sezione di Torino, Torino, Italy
High Energy Accelerator Research Organization (KEK), Tsukuba, 305-0801, Japan
Dipartimento di Fisica Generale, Universita' di Torino, Torino, Italy
Department of Physics, Kyoto University, Kyoto, 606-8502, Japan
Department of Physics, The University of Tokyo, Tokyo, 113-0033, Japan
Research Center for Nuclear Physics (RCNP), Osaka University, Osaka, 567-0047, Japan
Laboratory of Physics, Osaka Electro-Communication University, Osaka, 572-8530, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, 152-8551, Japan
Department of Physics, Osaka University, Osaka, 560-0043, Japan
Technische Universita¨t Mu¨nchen, D-85748, Garching, Germany
Graduate School of Arts and Sciences, The University of Tokyo, Tokyo, 153-8902, Japan
ASRC, Japan Atomic Energy Agency, Ibaraki 319-1195, Japan
Department of Chemical Physics, Lund University, Lund, 221 00, Sweden
Department of Physics, Tohoku University, Sendai, 980-8578, Japan
Excellence Cluster Universe, Technische Universita¨t Mu¨nchen, D-85748, Garching, Germany
Korea Institute of Radiological and Medical Sciences (KIRAMS), Seoul, 139-706, South Korea

Appendix

Λ p + forward $n_{mis.}$ @ E15 1st



Prog. Theor. Exp. Phys. 2016, 051D01 (11 pages)
DOI: 10.1093/ptep/ptw040

invariant mass of Λp

$\sigma_M(\Lambda p) \sim 10$ MeV/c²

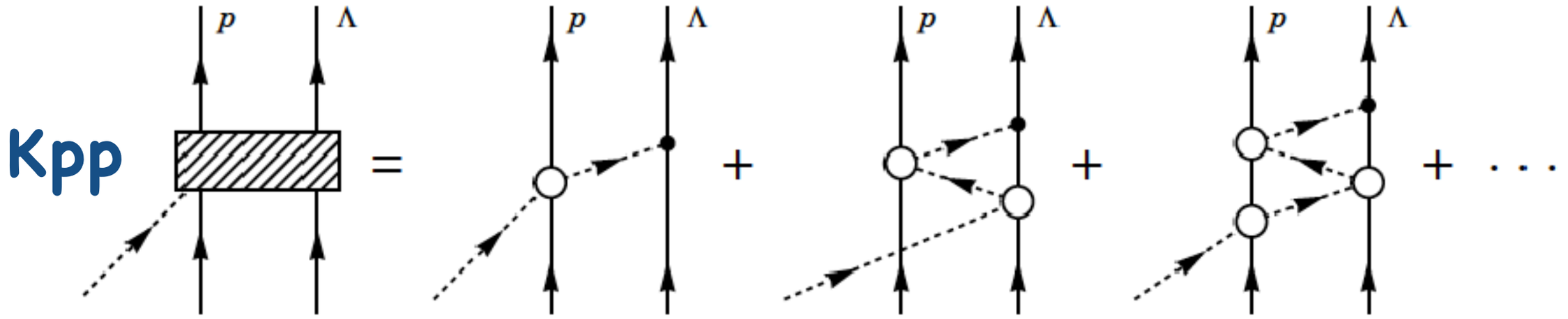
Higher statistics @ E15^{2nd}

(Λ p)$_{CDS}$ + forward n

in parallel to the 2nd run

Λp + $n_{mis.}$ vs. theory

Structure in E15[1st] can be explained with quasi-free K absorption (QF_{KA}) & Kpp @ χ-UM?



Sekihara Oset Ramos

PTEP

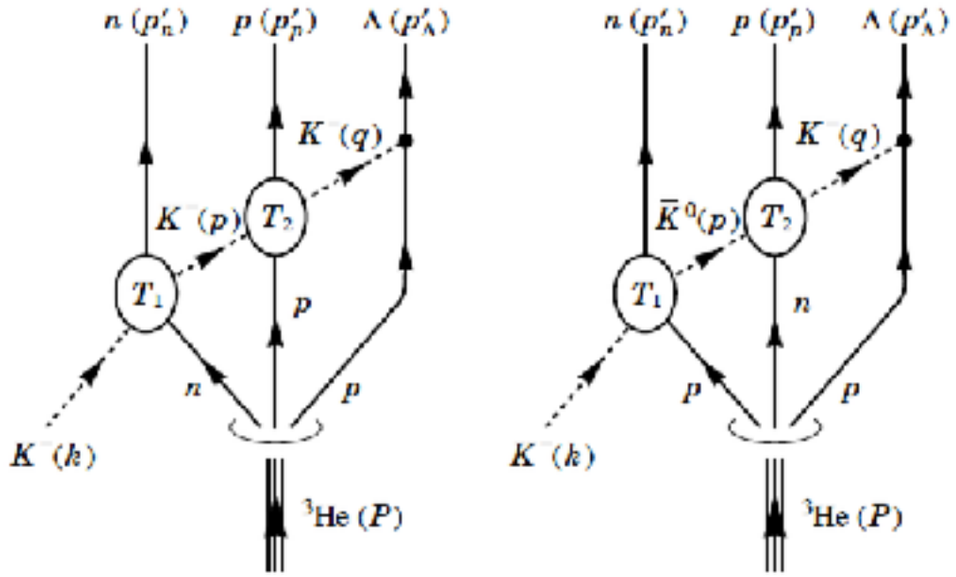
Prog. Theor. Exp. Phys. 2016, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166

On the structure observed in the in-flight ^{3}He(K^-, Λp)n reaction at J-PARC

Takayasu Sekihara[1,*], Eulogio Oset[2], and Angels Ramos[3]

[1]*Advanced Science Research Center, Japan Atomic Energy Agency, Shirakata, Tokai, Ibaraki 319-1195, Japan*
[2]*Departamento de Física Teórica and IFIC, Centro Mixto Universidad de Valencia-CSIC, Institutos de Investigación de Paterna, Aptdo. 22085, 46071 Valencia, Spain*
[3]*Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona, Martí i Franquès 1, 08028 Barcelona, Spain*
*E-mail: sekihara@post.j-parc.jp

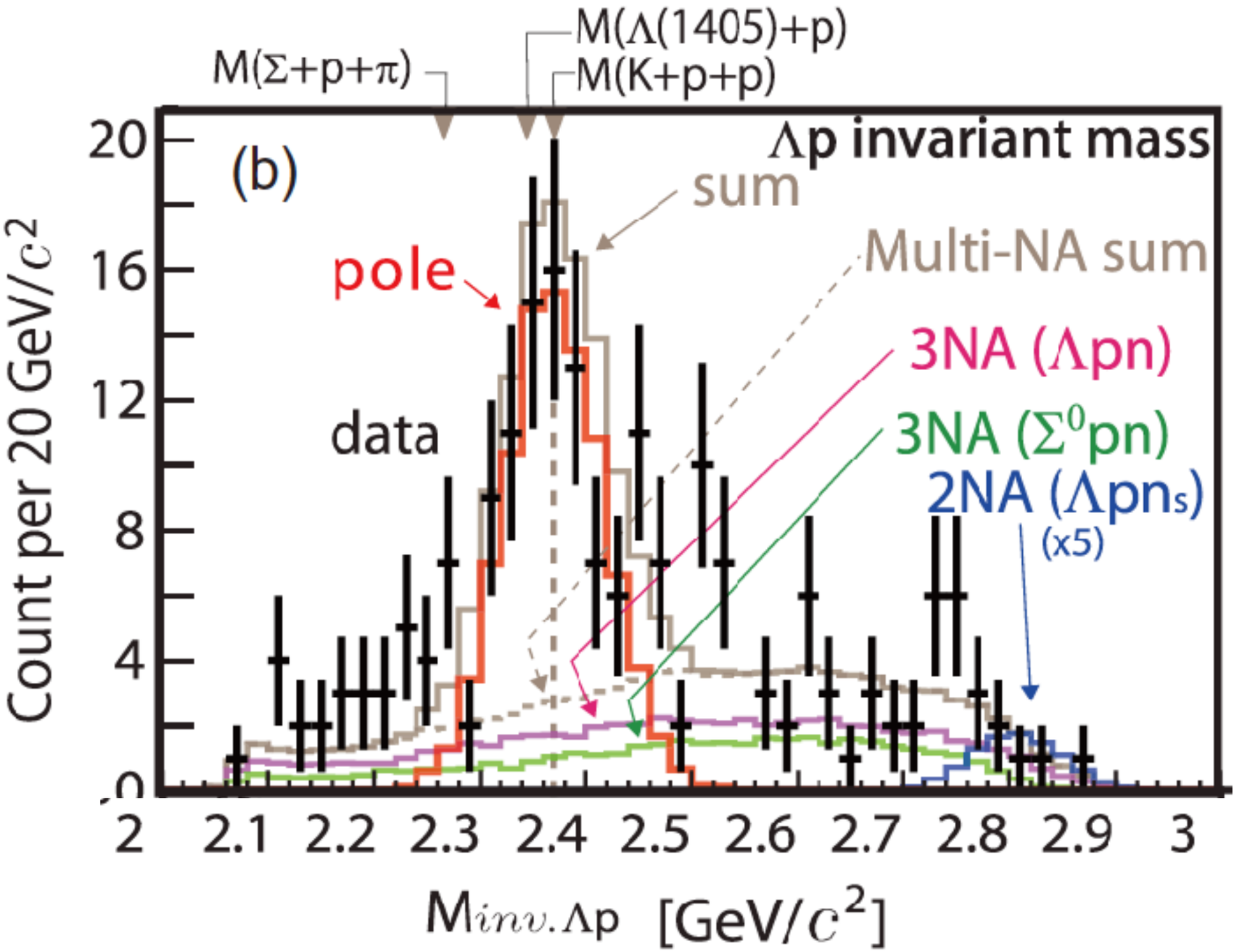
Received July 11, 2016; Revised October 7, 2016; Accepted October 15, 2016; Published December 30, 2016



$QF_{\bar{K}A}$

in parallel to the 2nd run

Λp + $n_{mis.}$ vs. theory

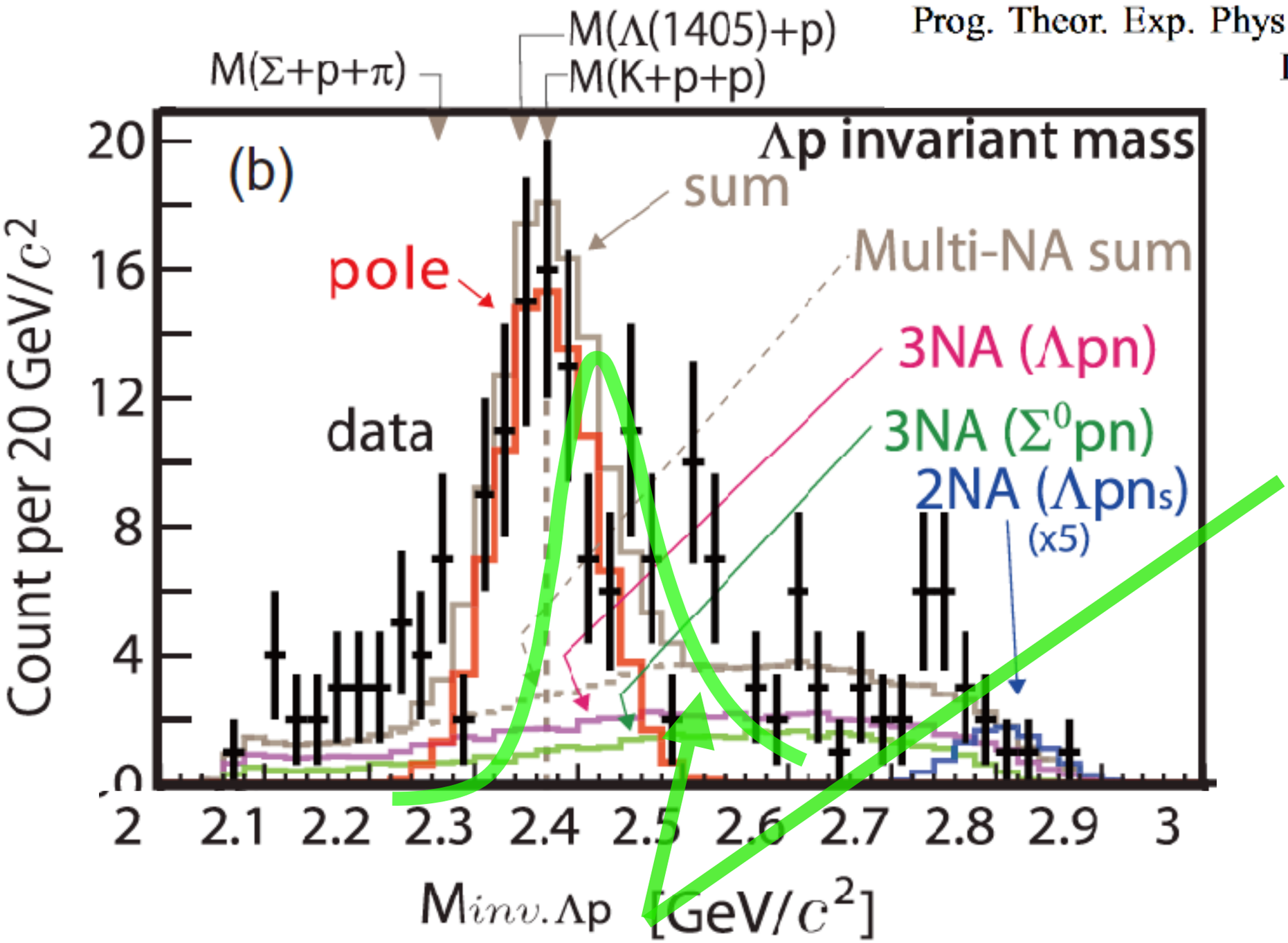


in parallel to the 2nd run

Λp + $n_{mis.}$ vs. theory

Sekihara-Oset-Ramos

Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166



$QF_{\bar{K}A}$ only

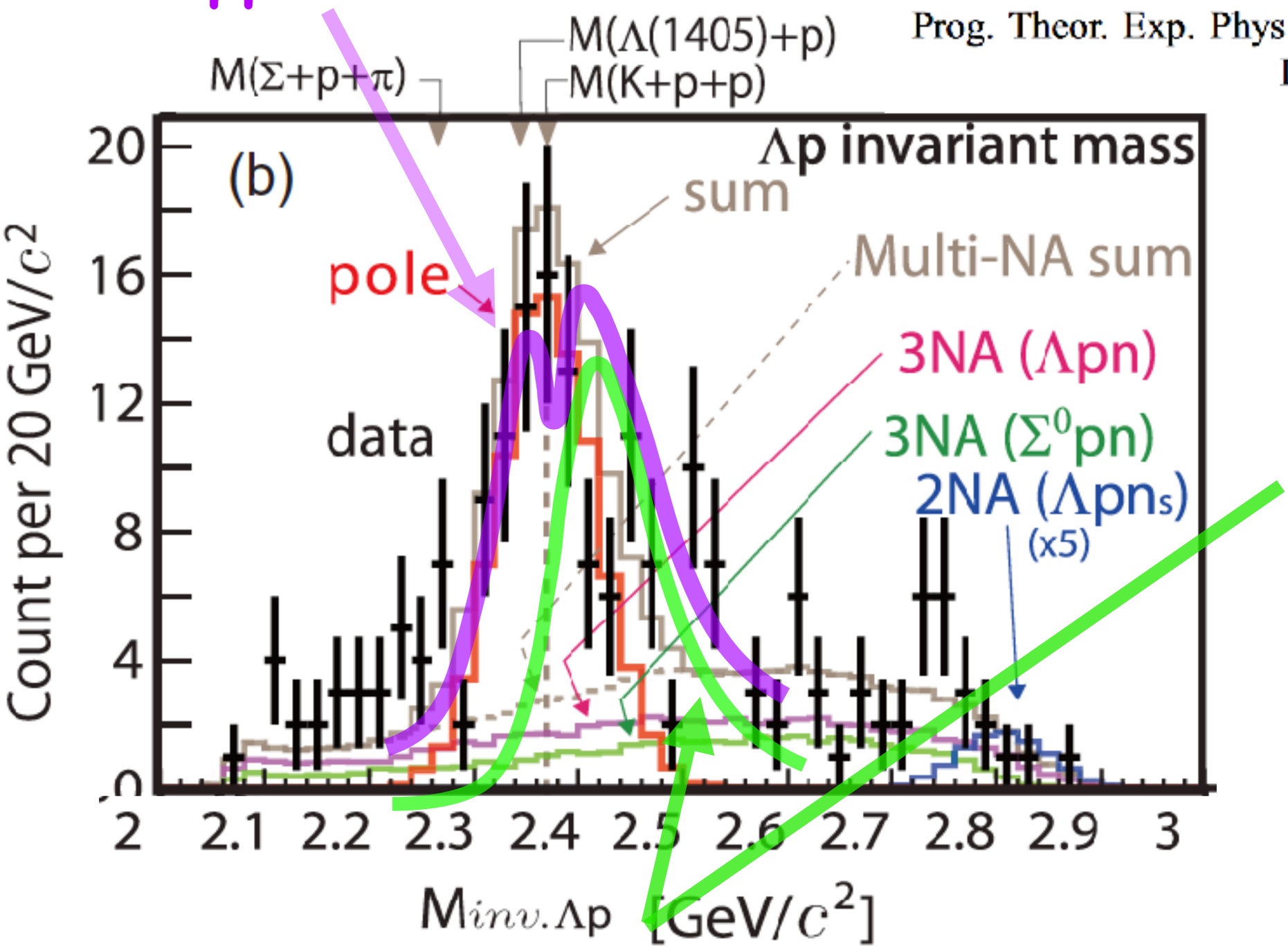
in parallel to the 2nd run

Λp + $n_{mis.}$ vs. theory

"Kpp" + $QF_{\bar{K}A}$

Sekihara-Oset-Ramos

Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166



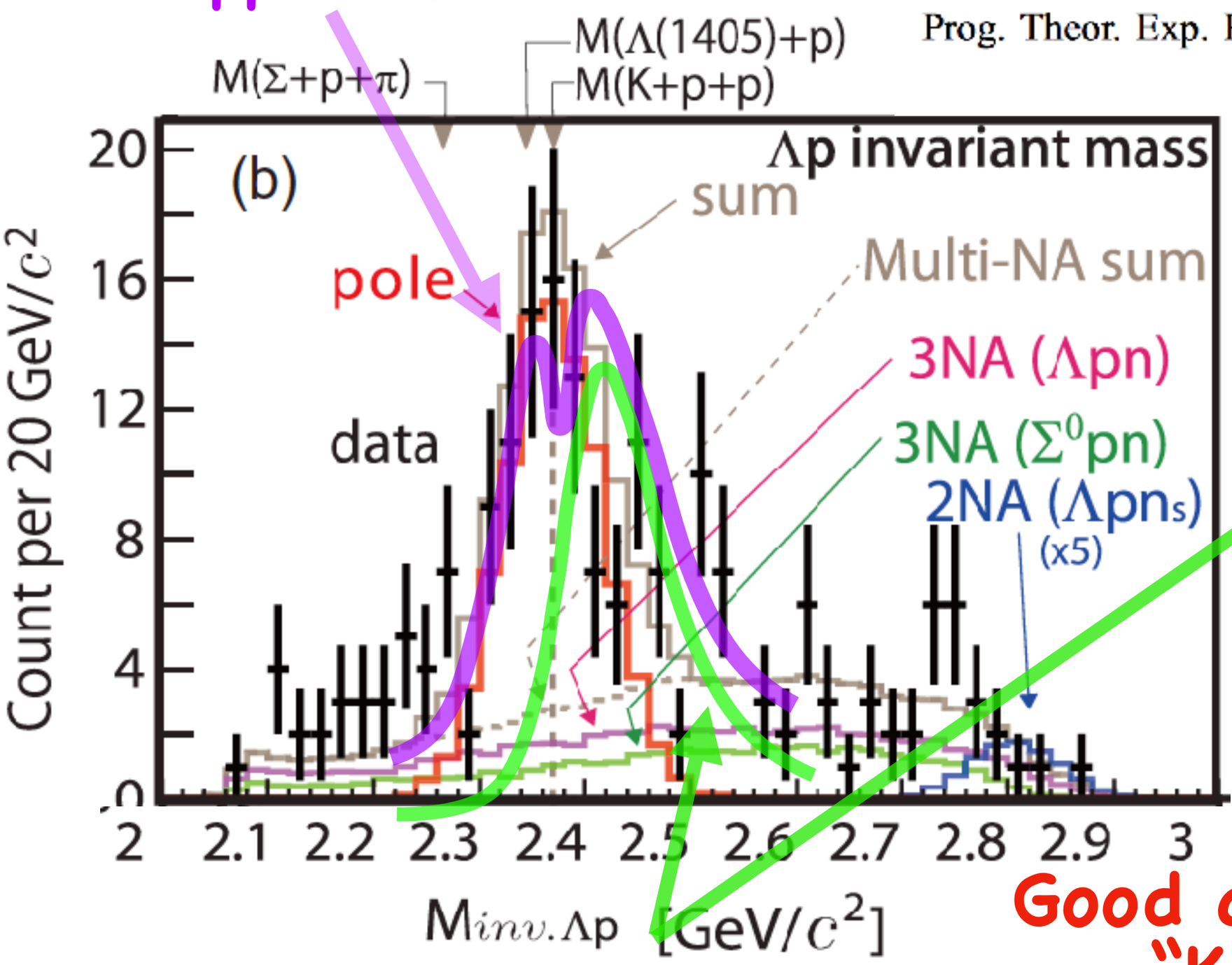
in parallel to the 2nd run

Λp + $n_{mis.}$ vs. theory

"Kpp" + $QF_{\bar{K}A}$

Sekihara-Oset-Ramos

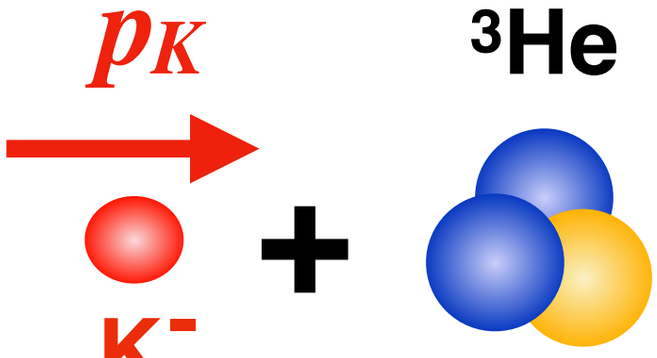
Prog. Theor. Exp. Phys. **2016**, 123D03 (27 pages)
DOI: 10.1093/ptep/ptw166



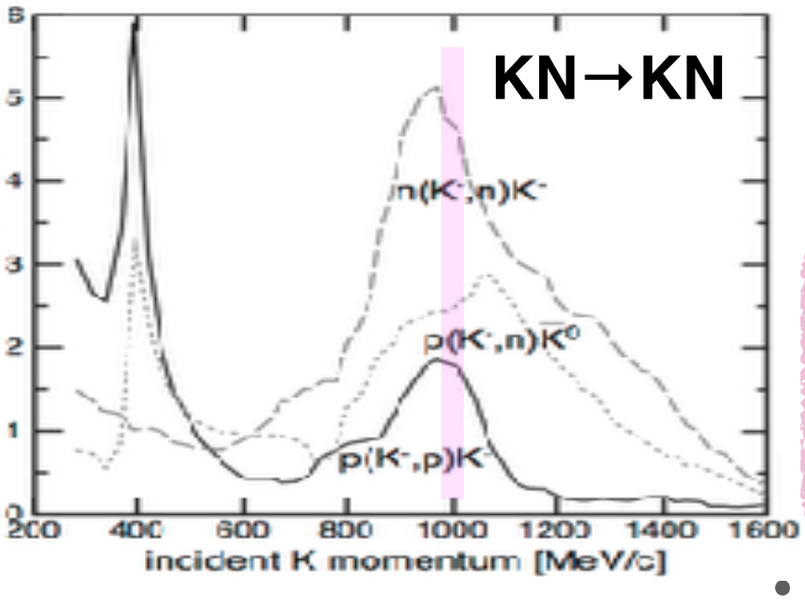
$QF_{\bar{K}A}$ only

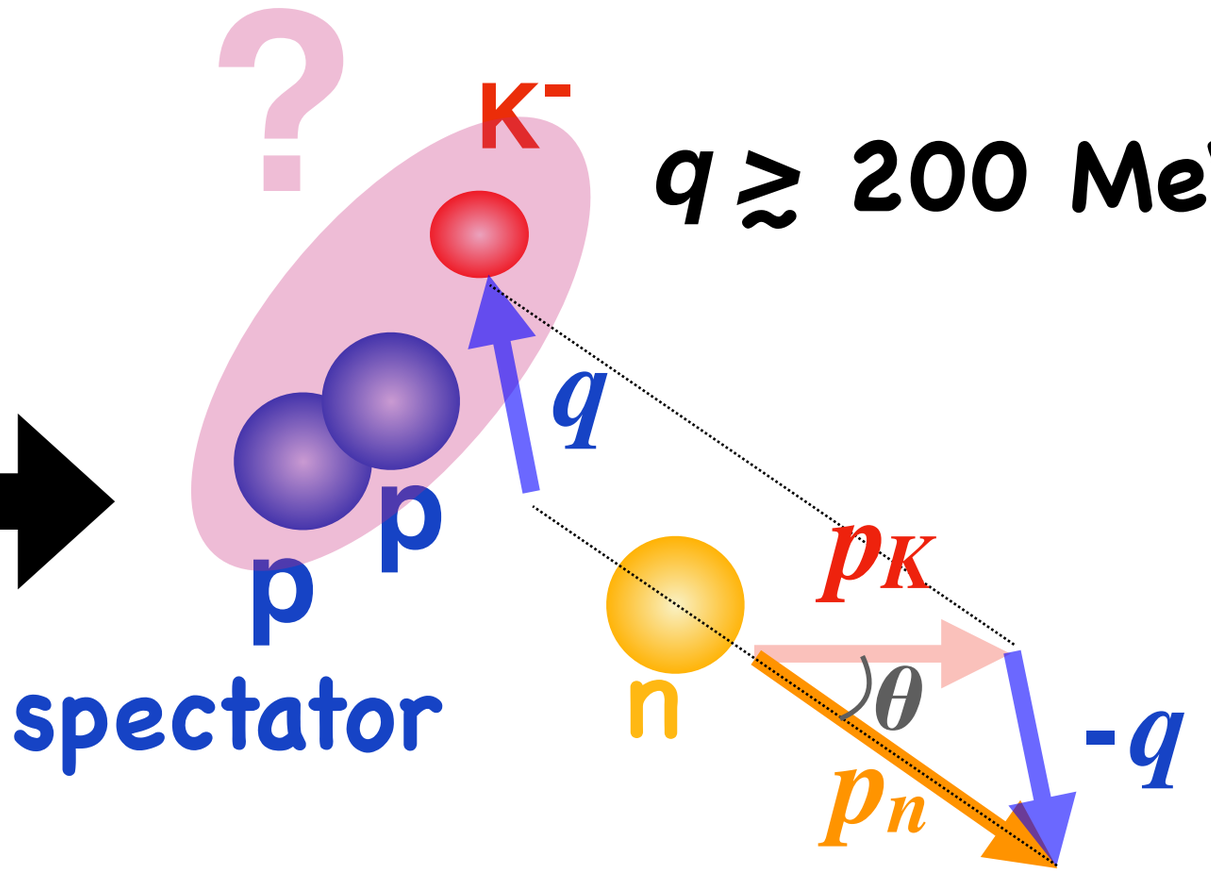
Good agreement! for "Kpp" + $QF_{\bar{K}A}$

Kinematics



1 GeV/c
($\sqrt{s_{KN}}$ ~ 1.8 GeV)





$q \gtrsim$ 200 MeV/c

K$^-$ + ^{3}He ➡ "?" + n

opening angle

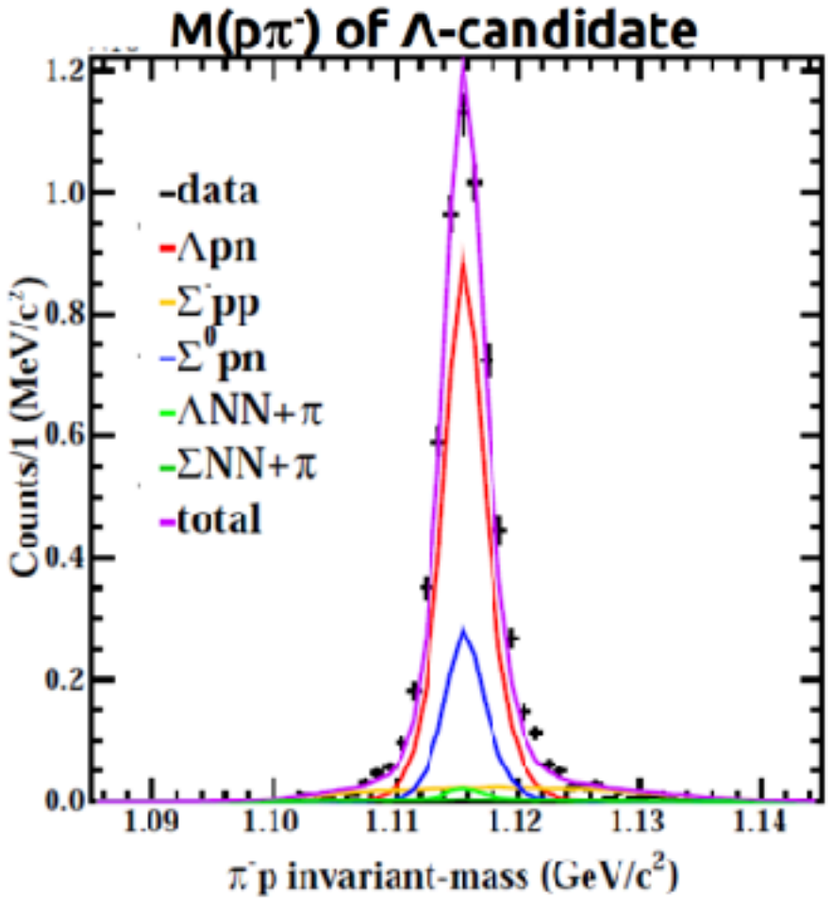
$q \longleftrightarrow \theta$ unique for given $M_{inv.}$"?"

momentum transfer

Λpn event selection (present logic)

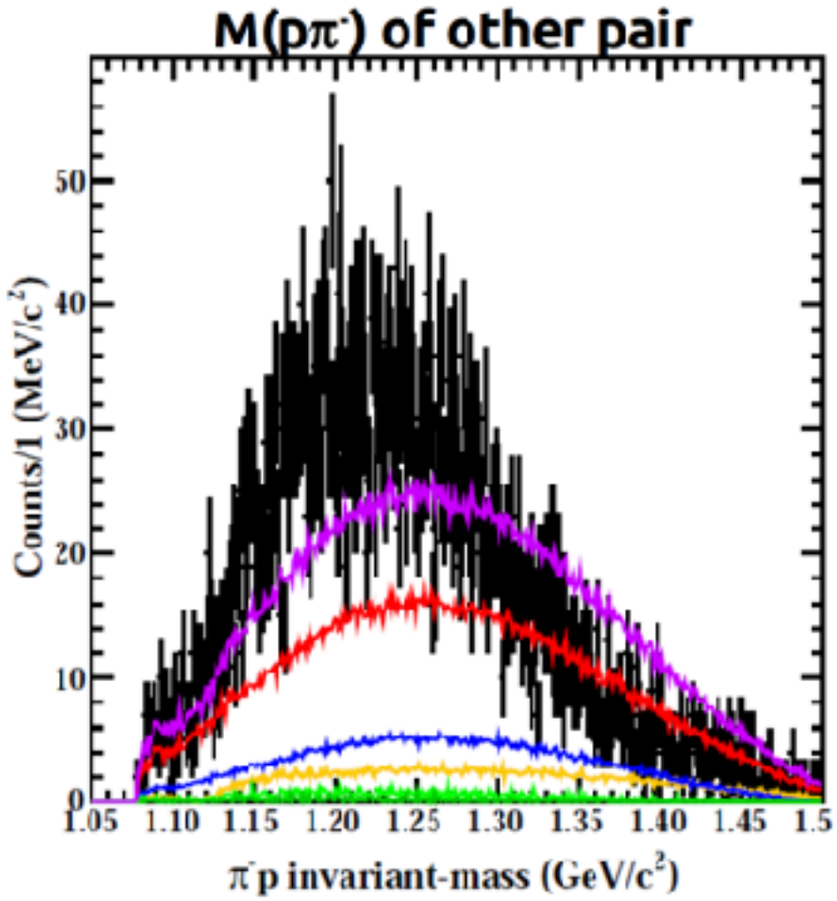
pπ⁻ invariant mass

After Λpn event selection



correct Λ→pπ⁻ pair

(smaller lnL)



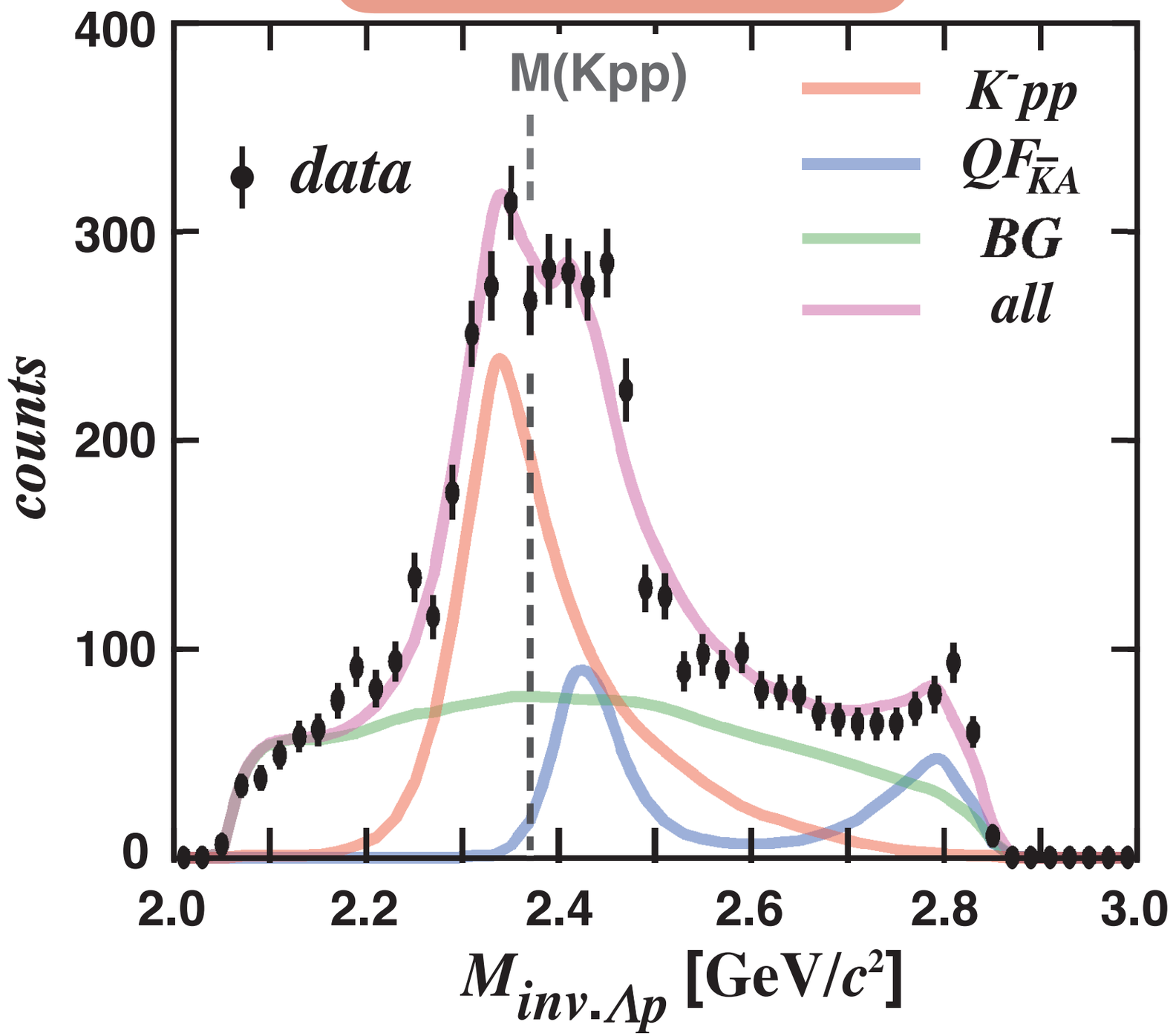
wrong pπ⁻ pair

(larger lnL)

$M_{inv.\Lambda p}$ $n_{mis.}$ + Λ p

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

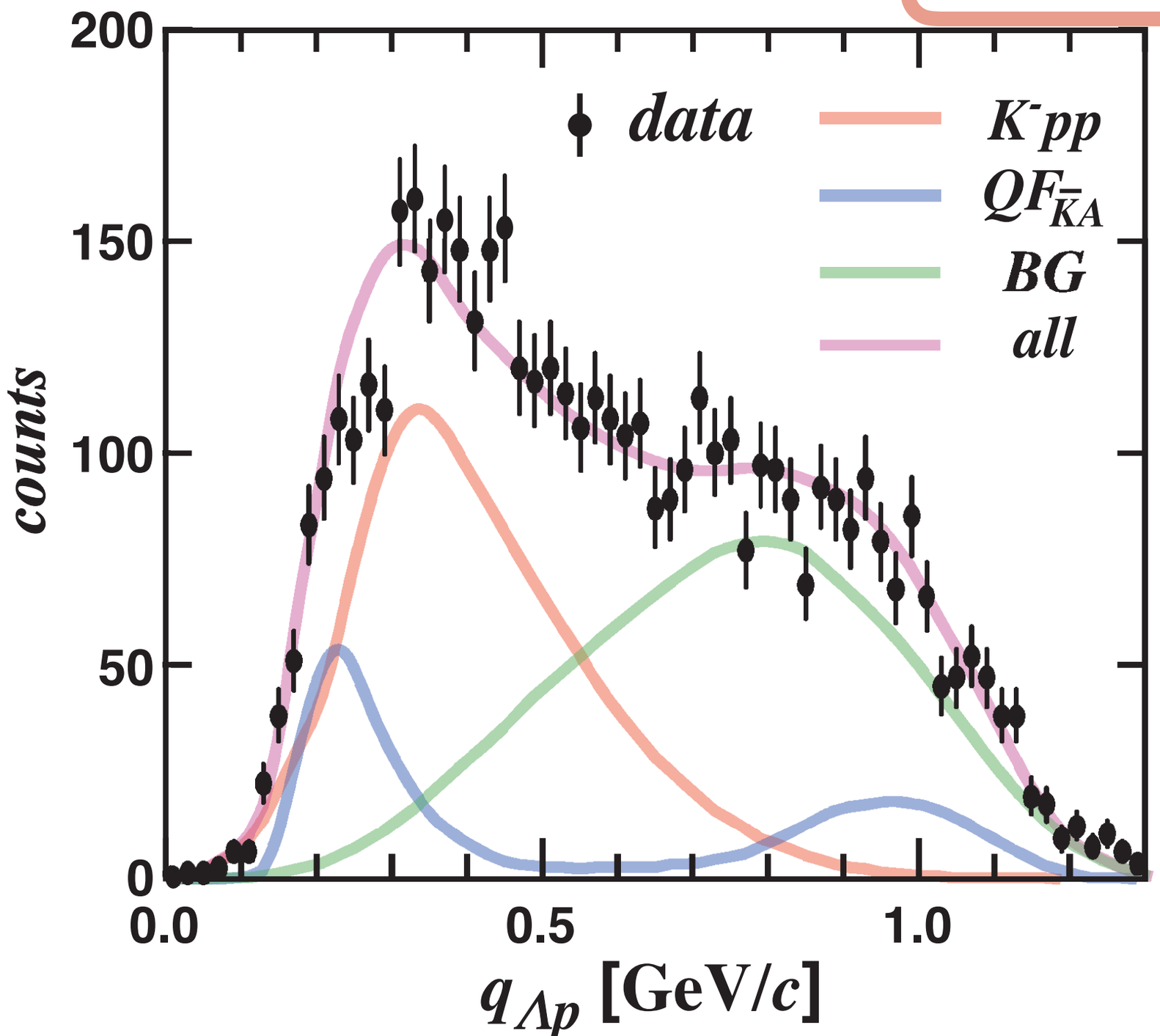
M spectrum



$M_{inv.\Lambda p}$ $n_{mis.}$ + Λ p

$$\rho_{3B}(M,q) \times \mathcal{E}(M,q) \times \frac{\left(\Gamma_{Kpp}/2\right)^2}{\left(M - M_{Kpp}\right)^2 + \left(\Gamma_{Kpp}/2\right)^2} \times \exp\left(-\frac{q^2}{Q_{Kpp}^2}\right)$$

q spectrum



Λ*(πΣ)p*n* Events

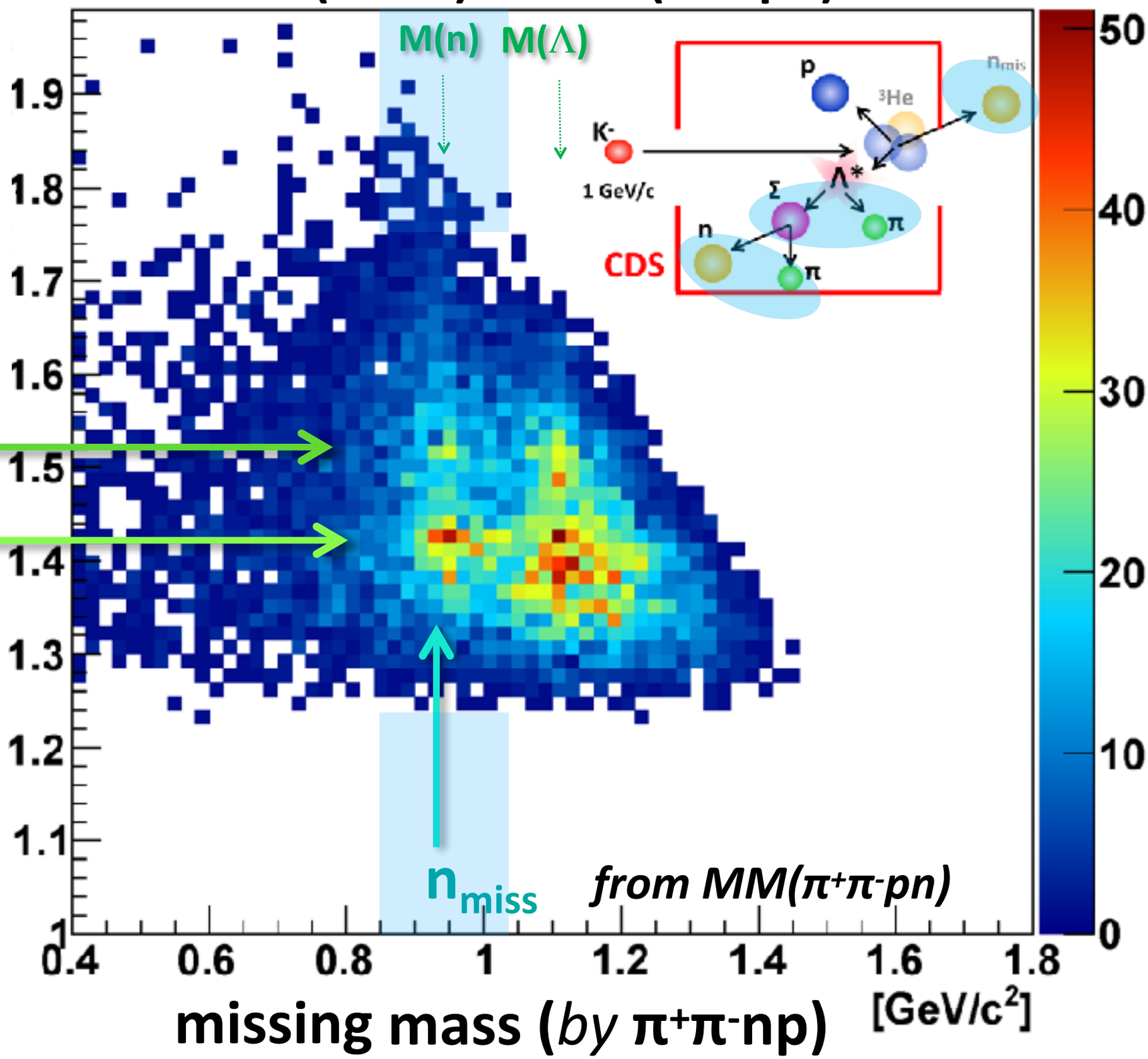
F. Sakuma

Λ* mass

(*by* π⁺(π⁻n)

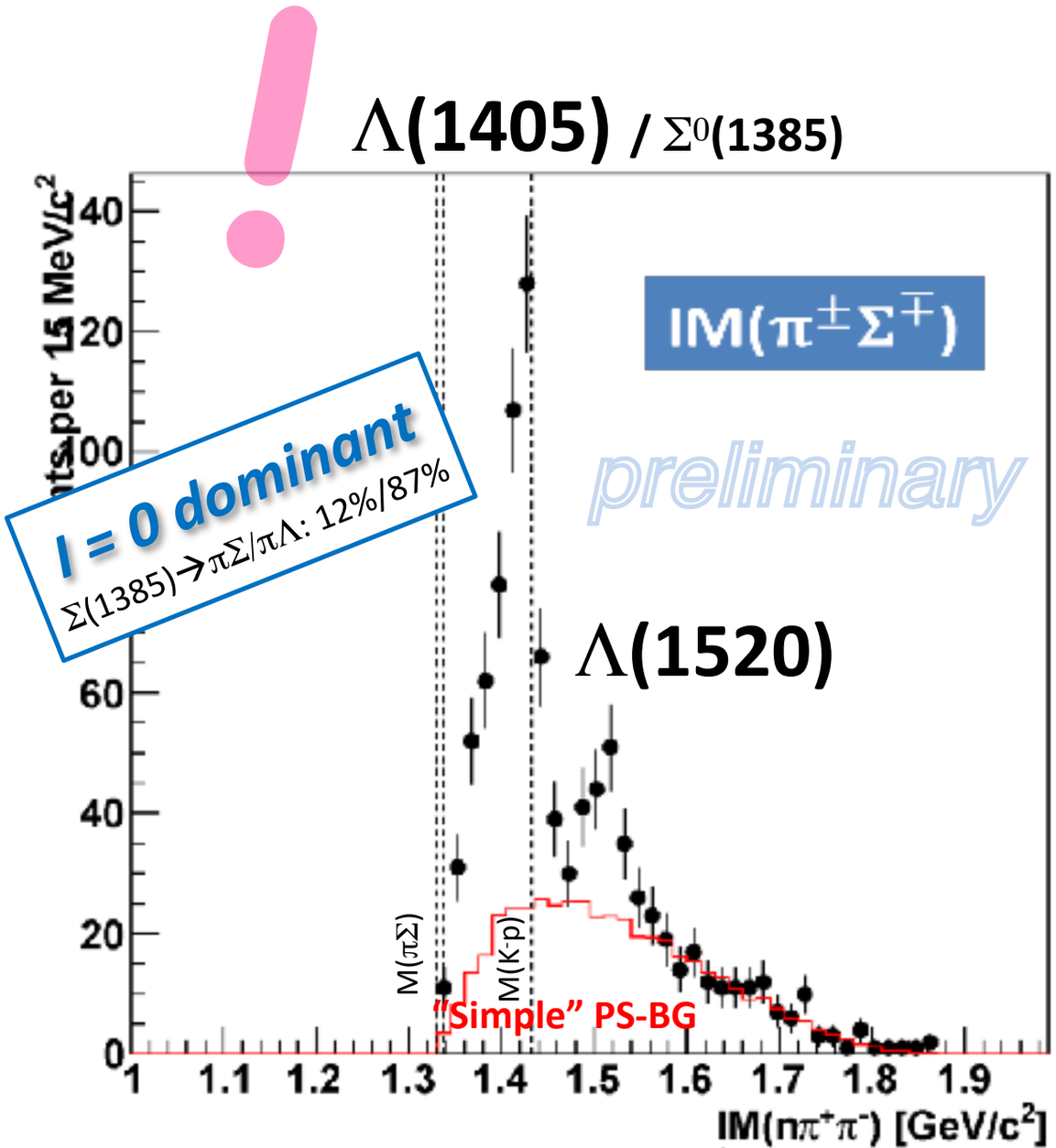
***or* π⁻(π⁺n))**

IM(nπ⁺π⁻) vs MM(π⁺π⁻pn)

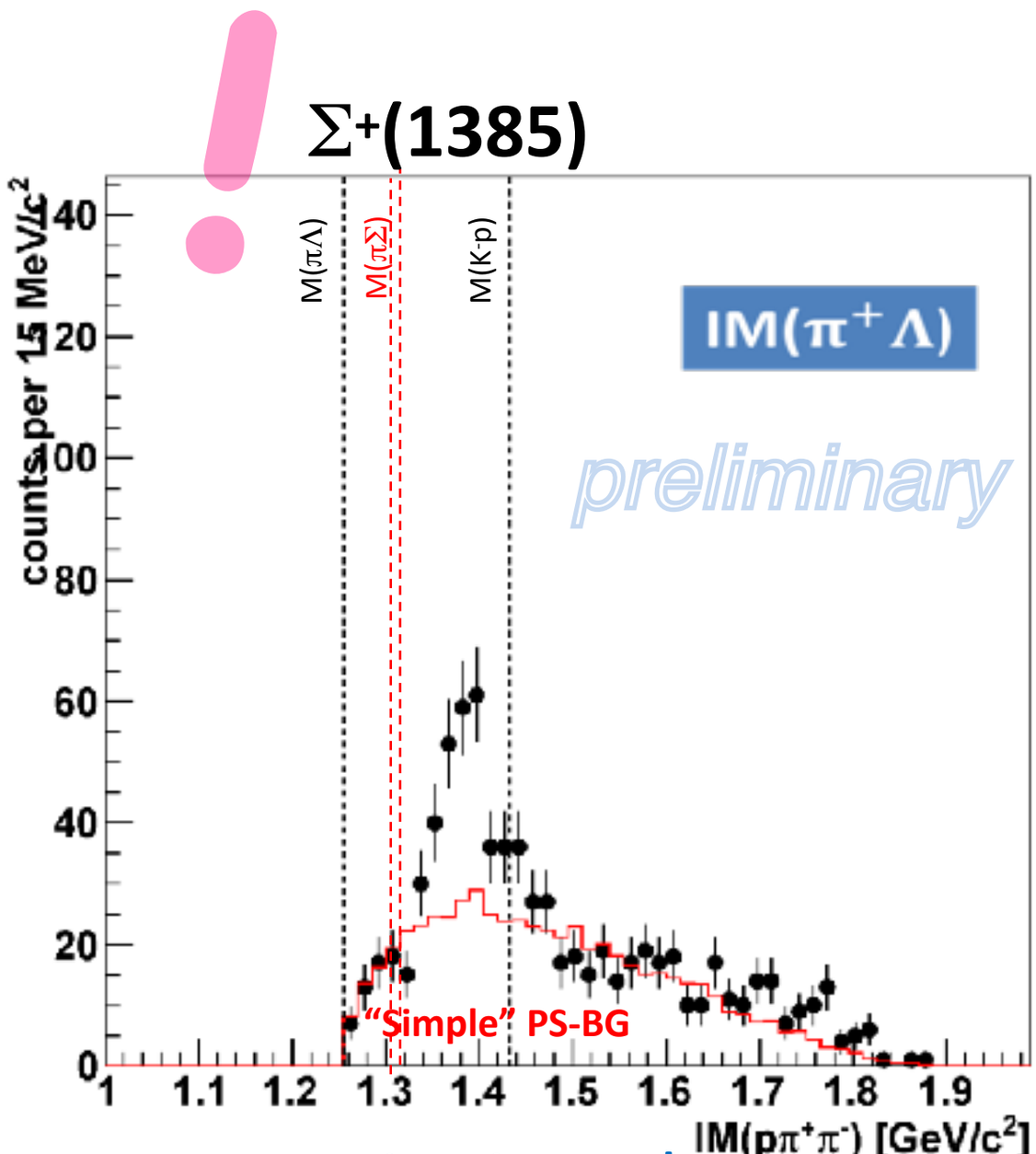


missing mass (*by* π⁺π⁻np)

Λ*(πΣ)p*n* *vs.* Σ*⁺(π⁺Λ)n*n*



I =0 and 1 mode **Λ* mass**



I = 1 mode **Σ* mass**

Λpn event selection (previous logic)

Improving statistics via "ppπ⁻ trigger"

$$K^- + {}^3He \rightarrow ? \rightarrow \Lambda + p + n$$

$$K^- + {}^3He \rightarrow Y + n$$
$$Y(=K^- pp) \rightarrow \Lambda + p$$

$$K^- + {}^3He \rightarrow \Lambda + p + X_{mis}\ (X_{mis}=n)$$